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"DISEÑO E IMPLEMENTACION DE UN CONTROLADOR DE VELOCIDAD DE MOTORES DE CORRIENTE ALTERNA MONOFÁSICOS"

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ABSTRACT

This thesis is about speed control of small domestic AC motors which will be used for home automation applications. First of all, a literature study about the different types of motor for domestic applications is carried out, which has led us to choose a Permanent Split Capacitor (PSC) motor to use in this project.

Later, a literature study is performed about various methods of controlling the speed of the PSC motors and come to the conclusion that the best solution is using a three-phase inverter bridge.

It is required the design of the motor controller, therefore an electric drive to vary the PSC motor speed was designed using the topology of a three-phase voltage source inverter (VSI). This system allows varying the induction motors speed, varying the frequency and voltage. It was made implementing PWM (Pulse Width Modulation) control algorithms in a PIC microcontroller. The PIC microcontroller generates the control signals which are firstly sent to the optocouplers, which achieve the isolation between the control system and the power system.

Optocoupler output signals are sent to the MOSFETs driver and finally to the MOSFETs, where DC bus (generated by a rectifier) is synthesized to provide two sinusoidal voltages at 90 degrees out of phase with varying amplitude and varying frequency to fed the motor, according to the V/f profile.

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Chapter 1: Introduction

1.1. Context

Nowadays, electrical machines play an important role in industry and daily life of human beings. An electrical machine converts mechanical energy into electrical energy and vice versa. Talking about the supply of the electrical machines, there are two types: alternating current machines (AC) and direct current machines (DC). Also, AC machines are divided into, synchronous machines and induction machines [1, 2, 5].

One of the most used machines today is the induction motor. The induction motor is a rotating machine designed to operate with a three-phase or single-phase alternating voltage supply. The induction machine is mainly composed of two elements: the stator and rotor. There are two different types of rotors that can be arranged within the induction motor stator, squirrel cage rotor and wound rotor. The most common type of induction motor is the squirrel cage rotor [3, 4, 5, 7].

Much of the equipment and processes used in modern industry are loads driven by electrical motors that often need to run at a speed that varies according to the operation they are performing. The speed in some cases such as pumping or trains may need to be changed dynamically to suit the conditions and in other cases it may only change as the duty of the load progresses. These devices require precise speed control to achieve suitable productivity, good finalization of the manufactured product, or to ensure the safety of the workers and the equipment itself as well [5, 6].

Various techniques used in the past for controlling the speed of AC induction motors are available and often the use of auxiliary rotating machines may be necessary. These auxiliary machines have now been supplanted by static AC variable speed drives using various types of power semiconductor, operating as electrically controlled switches. Variable speed drive is a controller for induction motor that energized, protects and allows varying the motor speed without extra accessory between motor and load. The main advantage is the high efficiency which is attained because of the little "on-state" conduction losses when the power semiconductor is conducting the load current and the low "off-state" leakage losses when the power semiconductor is blocking the source, or load, voltage; resulting in considerable reductions in operating costs.

The main devices in the operation and techniques of the modern variable speed control of induction motors are:

- Rectifiers
- Gate Drivers (Driver)
- Optocouplers
- Microcontrollers
- Inverters

The rectifier is a circuit that converts an AC signal into a signal DC unidirectional and is classified as single and three phases. The inverter is a circuit that converts a DC voltage to AC voltage. With inverter is possible to generate voltages in determinate amplitudes and frequencies by using a modulation technique called Pulse Width Modulation (PWM) [1, 2, 6].

Inverters can be classified basically into two types

- Single-Phase inverters.
- Three-Phase inverters.

And these in turn:

- Voltage source inverters (VSI).
- Current source inverters (CSI).

For example, three-phase inverter consists of three arms or legs, where the half-bridge upper and lower switches are controlled complementarily. As turning off time is greater than the turning on time, it is necessary to include a dead time between turning off of one of the half bridge transistors and the turning on of the other.

In ideal inverters, waveforms of output voltage should be sinusoidal. However, real inverters are not sinusoidal and contain certain amount of harmonics. Given the current availability of power semiconductors devices, you can minimize or significantly reduce the harmonic content of output voltage by switching techniques.

Most power devices used in inverter motor control applications are IGBTs or MOSFETs (Insulated Gate Bipolar Transistor and Metal Oxide Semiconductor Field-Effect Transistors respectively).

A power MOSFET is a voltage-controlled transistor. It has a little drop voltage and therefore low losses compared to other transistors, but the saturation and temperature sensitivity limit it to certain applications. The IGBT is a bipolar transistor controlled by a FET that required a minimum current for operation; its switching time is very fast and is appropriate for high frequencies. Its disadvantage is the bipolar transistor voltage drop that causes higher conduction losses compared to the MOSFET [2, 6, 7].

The pulses that a switching power converter delivers to a motor are controlled by means of Pulse Width Modulated (PWM) signals applied to the gates of the power transistors. PWM signals are pulse trains with fixed frequency and amplitude and with variable pulse width. The width of these pulses changes from one period to another, according to a reference signal. When a PWM signal is applied to the gate of a power transistor, it causes the turn on-off intervals of the transistor to change from one PWM period to another PWM period according to the same reference signal. The frequency of a PWM signal (carrier) must be much higher than the frequency of the reference signal (fundamental frequency), such that the energy delivered to the motor and its load will depend mostly on the modulating signal [8].

Another major factor in AC drives technology is the availability of microprocessor / microcontroller for the control of AC induction motor. Microcontroller operates at an adequately high clock frequency to complete their calculations in adequate time to directly generate the control signals. In addition, the microprocessor can perform lower priority tasks, such as diagnostics, self-test, start-up and shutdown sequencing and fault monitoring.

1.2. Aims and Objectives

The objectives of this particular project are the following: realizing a literature study about different Ac induction motors, which are used in residential environment as our application (tubular shutters motors). Afterward, choosing the best for speed control and select the optimum technique for speed control and with this method; design an adjustable speed drive system for the chosen single-phase induction motor. Using a microcontroller for open-loop control system using the pulse width modulation techniques and to evaluate the relation among the speed and the audible noise. Furthermore, I cannot forget to take into account during the project, the next points: power efficiency, motor and controller reliability and flexibility, speed range, ease of programming, speed accuracy, power efficiency, robustness and obviously the cost of the controller.

1.3. State of the Art

Until the last decades of the twentieth century, AC machines tended to be used primarily as devices with just one speed available. The typical was that the machines operated from fixed frequency sources, in most cases using the mains of 50 or 60 Hz.

For AC motors, speed control requires a variable frequency supply and there were no such sources with ease. Therefore, for applications which require variable speed machines were used DC machines, which provide a highly flexible speed control, although at some cost, since they are more complex and require more maintenance particularly because of the brushes.

Availability of having solid state switches completely changed this scenario. It is now possible to build devices based on Power Electronics capable of supplying the voltage-current drive, with variable frequency required to achieve the behavior of variable speed for AC machines. Currently, AC machines have replaced the DC machines and has developed a wide range of new applications because of they are simpler and more economical in terms of maintenance.

During the past thirty five years has been a revolution in the applications for electric motors. The development of packages of solid state drives for motors has progressed to such an extent that almost any power control problem can be solved using them. With such solid state drives can handle DC motors with AC power sources and AC motors with DC power sources. In the same way, you can change power from one frequency to power of another frequency.

In addition, the costs of solid state drives have drastically reduced while reliability has increased. The versatility and relative low cost of the controls and solid state drives have generated many new applications for AC motors in which they have behaviors that are normally associated with DC machines, which also have gained flexibility through the implementation of solid state drives. This big change has been thanks of the development and improvement of a series of solid state drives, in other words the Power Electronics.

Rotary electric machine is the fundamental electromechanical device of electric drives systems. The drive systems are widely used in various applications such as pumps, fans, mills paper and textiles, elevators, electric vehicles and ground transportation, appliances, wind generation systems, servos and robots computer peripherals, steel and cement mills, marine propulsion, including others [1, 4, 5, 7].

Chapter 2: AC induction motors

AC induction motors are the most widely used type of electronic motor in the current world. AC induction motors are primarily used as a source of constant speed mechanical power and they are being used more and more in variable speed control applications. They are popular because they can provide rotary power with high efficiency; no commutation is required, lighter in weight, simple and sturdy design, low maintenance and exceptional reliability, with relativity low cost.

These desirable qualities are the result of two factors:

1. AC motors can use the AC power.
2. Most AC motors do not need brushes as in DC motors.

In most cases, the AC source power is connected only to motor's stationary windings. Rotor gets its power by electromagnetic induction; a process that does not require physical contact. Maintenance is reduced because the brushes do not have to be periodically replaced. In addition, motor tends to be more reliable and last longer because parts malfunctioning are minimal and there is no "brush dust" to contaminate the bearings or windings [2, 7].

2.1. Basic construction and operating principle

Such as the most motors, an AC induction motor has a fixed outer portion, called the stator and the rotor that spins inside with a carefully engineered air gap between the two.

Basically all electrical motors use magnetic field rotation to spin their rotors. A three-phase AC induction motor is the only type where rotating magnetic field is created naturally in the stator because of the nature of the supply. While a single-phase AC induction motor depends on extra electrical components to produce this rotating magnetic field.

The induction machine in a stop condition, with the stator winding connected to three-phase source and the rotor windings short-circuited at both ends is equivalent to a static transformer with short-circuited secondary windings. Magnetic fields produced because of the AC supply connected to stator windings, generates a rotating magnetic field that cuts the rotor windings, this magnetic field rotates at synchronous speed. This rotating field induces Electromotive Force (EMF) in the rotor circuit, according to the Faraday's law of induction.

$$\xi = -\frac{d\phi}{dt} \qquad (2.1)$$

Where:
ξ *= Induced Electromotive Force [V].*
$\frac{d\phi}{dt}$ *= the rate of change of flux.*
The minus sign indicates the direction of the induced Electromotive Force is such that any current produced by it tends to oppose the change in fluxm which is known as the Lenz's Law.

Thus, this induced voltage provoke that a determined current flows through the rotor. These induced currents in the rotor generate another rotating magnetic field regard to the rotor. This rotating magnetic field created by the rotor interacts with the rotating magnetic field created by the stator and in effect generates torque. As a result, motor rotates in the direction of the resultant torque [7, 9].

2.1.1. Stator

The stator is the outer body of the motor which houses driven windings on an iron core. The stator core is made up of a stack of round pre-punched laminations pressed into a frame which may be made of aluminum or cast iron. The laminations are basically round with a round hollow inside through which the rotor is positioned. The inner surface of the stator is made up of a number of deep slots. It is into these slots that windings are positioned. The arrangement of the windings or coils within the stator determines the number of poles that the motor has. Internally they are connected in such a way, that on applying AC supply, a rotating magnetic field is created. Definitively, the stator consists of one electric circuit and other magnetic.

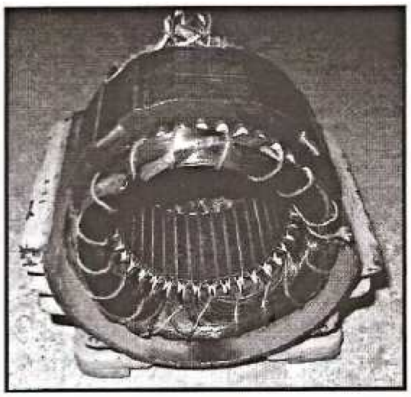

Figure 2.1 Induction motor stator

The winding configuration, slot configuration and lamination steel all have an effect on the performance of the motor. Voltage rating of the motor is determined by the number of turns on the stator and power rating of the motor is determined by the losses which comprise copper loss and iron loss and the ability of the motor to dissipate heat generated by these losses. The stator design determines the rated speed of the motor and most of the full load, full speed characteristics [4, 7, 9]

2.1.2. Rotor

The rotor is the inner body of the motor, which obviously is the rotating component. There are two types of rotor: squirrel cage rotor and wound rotor with slip rings. Most popular rotor is squirrel cage rotor, for instance almost 90% of induction motors have squirrel cage rotors. This is because squirrel cage rotor has a simple, cheap and rugged construction. In addition it has not slip rings and brushes, which means better reliability and long service life.

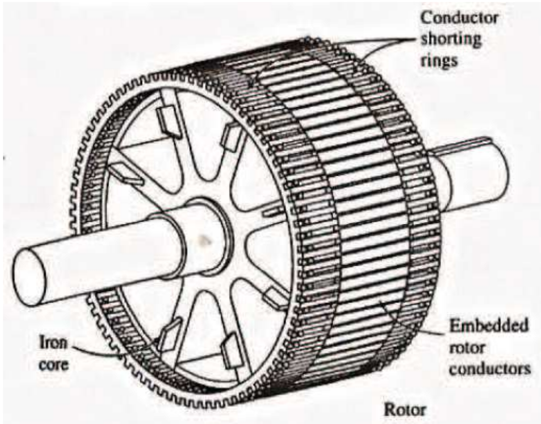

Figure 2.2 Squirrel cage rotor

The rotor is made up of several thin steel laminations with evenly spaced bars, which are made up of aluminum or copper, along the periphery. These bars are connected at ends mechanically and electrically by the use of rings. The rotor consists of a cylindrical laminated core with axially placed parallel slots for carrying the conductors. These rotor bars are permanently short-circuited at both ends by means of the end rings. This total assembly resembles the look of a squirrel cage, which gives the rotor its name. In addition, the rotor slots are not exactly parallel to the shaft, are placed at a small angle. There are two main reasons for skew the rotor slots:

1. Fulfill to run the motor in a quietly way by reducing magnetic hum and to decrease slot harmonics.
2. Reduce the locking tendency of the rotor. The rotor teeth tend to remain locked under the stator teeth due to direct magnetic attraction between the two. This happens when the number of stator teeth is equal to the number of rotor teeth.

Figure 2.3 Rotor skew

Rotor is mounted on the shaft using bearings on each end; one end of the shaft is normally kept longer than the other for driving the load. Some motors may have an accessory shaft on the non-driving end for mounting speed or position sensing devices [4, 7, 9].

2.1.3. Speed of an induction motor

The magnetic field created in the stator rotates at a synchronous speed (n_s).

$$\boldsymbol{n_s = 60 \times \frac{f}{P}} \qquad (2.2)$$

Where:
n_s = the synchronous speed of the stator magnetic field in RPM.
P = the number of pair of poles on the stator.
f = the supply frequency in Hertz.

The magnetic field produced in the rotor because of the induced current is alternating in nature. To reduce the relative speed, with regard to the stator, the rotor starts running in the same direction as that of the stator field and tries to catch up with the rotating electromagnetic field. However, in practice, the rotor never succeeds in "catching up" to the stator field. The rotor runs slower than the speed of the stator field. This speed is called the Rotor Speed (n_r).

The difference between n_s and n_r is called the "slip". The slip varies with the load. An increase in load will cause the rotor to slow down or increase slip. A decrease in load will cause the rotor to speed up or decrease slip. The slip is expressed as a percentage and can be determined with the following equation:

$$\boldsymbol{Slip = \frac{n_s - n_r}{n_s} \times 100}\ \% \qquad (\mathbf{2.3})$$

Where:
n_s = the synchronous speed in RPM.
n_r = the rotor speed in RPM.

The slip is a fundamental parameter in the induction motor. Its nominal value use to be between 0.02 and 0.04. Usually it is show as a percentage. For example: 4% slip means that speed of the motor is 96% of the synchronous speed [4, 7, 9].

2.1.4. Torque-speed characteristic

The torque developed (T) in a three-phase motor, ignoring the magnetizing inductance and the iron losses, for constant supply and frequency can be expressed in the next equation:

$$\boldsymbol{T = 3p\frac{V_s^2}{\left(R_s + \frac{R_r}{s}\right)^2 + X_e^2}\frac{R_r/s}{\omega_e}} \qquad (\mathbf{2.4})$$

Where:
T = The Developed torque.
p = The Pairs of poles.
V_s = The Supply voltage
R_s and R_r= The stator and rotor resistances respectively.
s = The slip.
X_e = Total leakage inductances.
ω_e = Electrical speed in radians.

Using the above equation, the variation of torque with speed (slip) can be plotted directly.

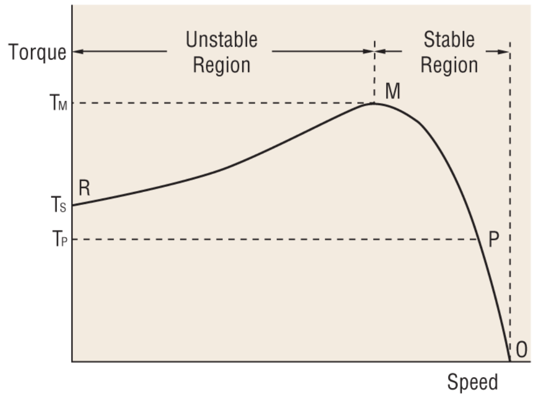

Figure 2.4 Torque-speed characteristic

As shown in figure 2.4, there are stable range and an unstable range in the Torque-speed characteristic. The area on the right is the stable one, because the system tends to return to its equilibrium point in case of any disruption. On the other hand, if the load torque cuts the motor curve in the left side, unstable area, any disruption destabilizes the system [4, 7, 9].

2.2. Single-phase vs. three-phase induction motors

Most induction motors used for industrial applications will have three-phase windings. Three-phase power source is widely available in an industrial environment. On the other hand, domestic environments usually only have single-phase power available, which presents a problem for three-phase induction motors.

A three-phase motor is the best type to use for variable speed control. The three-phase motor gives good torque performance at all operating speeds. Single-phase motors can also be used, but they have limited performance in the low-speed range. Depending on the motor, there can be significant torque pulsations when a single-phase induction motor is run at low speeds.

Like I said above, a three-phase motor can generate a rotating magnetic field in the stator windings when fed from a source of three-phase power. However, without some modification, an induction motor with a single stator winding cannot produce a rotating magnetic field that is capable of producing torque. This rotating field problem can be handled in different ways, as we will see in the following section [7, 10].

To sum up, this thesis is about motors in the residential environment, this means that the best choice is single-phase motor; consequently, it is the chosen one to uses in this project.

2.3. Single-phase induction motors

The need of single-phase induction motor is due to there are many facilities, both industrial and residential, where electrical company supplies only a single-phase power. Moreover, everywhere single-phase small motors are needed to push various household appliances such as sewing machines, drills, vacuum cleaners, air conditioners, washing machines, etc.

Most single phase motors are "small motors” of low power (less than 1 hp). There are also some motors with power between 1.5 and 10 hp for both 115 V and for 230 V sources phase and even for 440 V service within the limits of 7.5 to 10 hp. In addition, there are special motors with horsepower range from several hundred to even thousand hp for railway applications.

Single-phase induction motors has a serious disadvantage. This type of motor has only one stator winding, so the main magnetic field does not rotate, thus the torque necessary for the motor rotation is not generated. Hence, the single-phase induction motor is required to have a starting mechanism that can give the starting boost for the motor to rotate. Depending on the various start techniques, single-phase AC induction motors are further classified as described below [1].

2.3.1. Construction

In all single-phase induction motors, the rotor is the squirrel cage type, similar to polyphase induction motors; in fact, the rotor of any single-phase induction motor is interchangeable with some squirrel cage polyphase rotors.

Due to the fact that single-phase induction motors do not generate the starting boost to rotate by itself. There are two windings: the main and the auxiliary or starting winding, which are designed to produce the rotation of the rotor. Both the main and starting windings are distributed in slots uniformly spaced around the stator, but the starting winding slots are displaced 90 degrees regard to main winding [5].

2.3.2. Double revolving field theory

A single-phase AC power source supplies main winding that produces a pulsating magnetic field. This theory claims that, mathematically, the pulsating field could be divided into two fields of the constant magnitude, which are rotating in opposite directions and each field has a magnitude equal to half the maximum length of the original pulsating field.

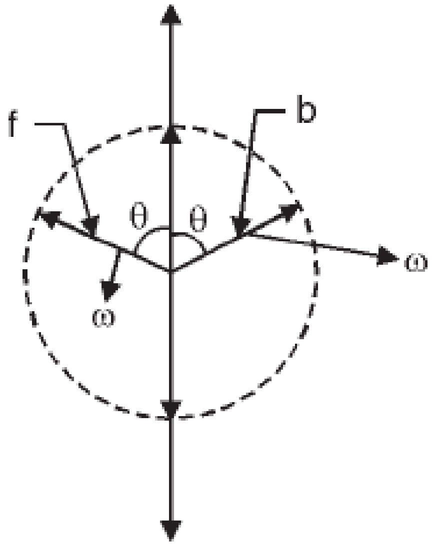

Figure 2.5 Representation of the pulsating field by space phasors.

These component waves rotate in opposite direction at synchronous speed. The forward (anticlockwise) and backward (clockwise) rotating field waves f and b are shown in figure 2.5. With the rotor stopped, the forward and backward fields produce equal torques but opposite in direction and hence no net torque is developed on the motor and the motor remains stationary. If the forward and backward air gap fields remained equal when the rotor is revolving, each of the component fields would produce a torque-speed characteristic similar to that of a polyphase induction motor with negligible leakage impedance as shown by the dashed curves f and b in figure 2.6.

The resultant torque-speed characteristic which is the algebraic sum of the two component curves shows that if the motor were started by auxiliary means it would produce torque in whatever direction it was started [4, 5].

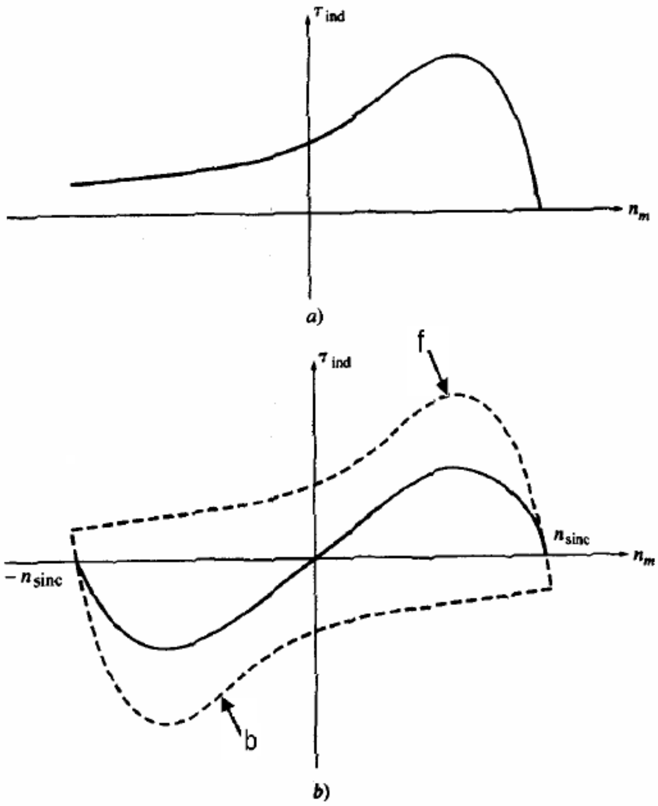

Figure 2.6 a) Torque-speed characteristic of a three-phase induction motor. b) torque-speed curves of the statoric magnetic fields and they rotate in opposite directions.

In any case, both the direct and inverse magnetic fields are present in a single-phase motor and both are produced by the same current. The two fields, are in series and each one provide to the motor, a part of the total voltage in the stator. Because of the presence of these fields, the direct rotating magnetic field (which has a high effective rotoric resistance) will limit the statoric current flow to the motor (which creates both fields, direct and inverse). Since the stator current provides the inverse statoric magnetic field is limited to a small value and that the inverse rotoric magnetic field is in a very large angle regard to inverse statoric magnetic field, the torque due to inverse fields is very small when the engine works near to synchronous speed. Figure 2.7 shows a more accurate torque-speed characteristic.

Besides the average net torque shows in the figure 2.7, there are torque pulsations at the double of the stator frequency. These pulsations are caused when the direct and inverse magnetic fields intersect, twice per cycle. Although these pulsations do not produce torque, increase the vibration and make the single-phase induction motors noisier than the three phase motors of the same size [5].

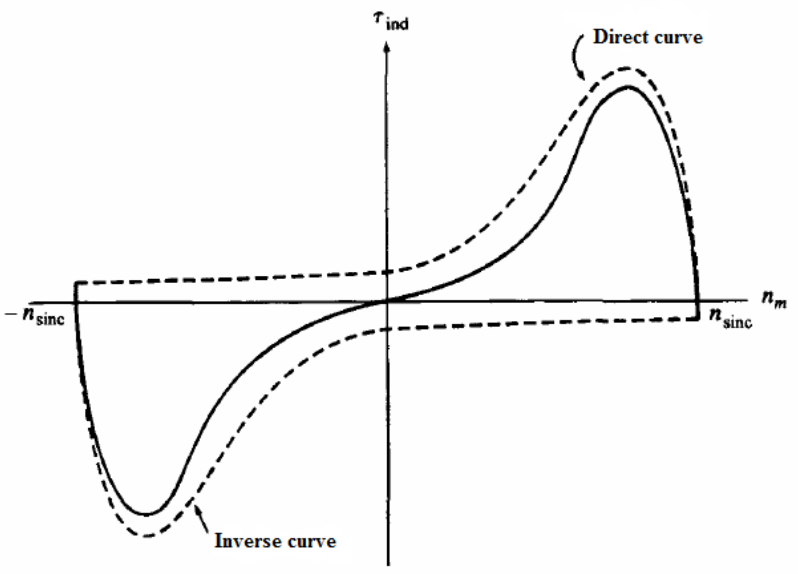

Figure 2.7 Torque-speed characteristic, with limitation of the current over the inverse rotating magnetic field.

2.4. Types of single-phase induction motors

As it was seen above, the single-phase induction motor does not have inherent starting torque. There are three techniques to attain that one of the two rotating magnetic fields would be stronger than the other, as a result, gives the starting boost to rotate in one or another direction:

1. Split-phase motors
2. Motors with capacitor
3. Shaded-pole motors

2.4.1. Split-phase motors

The split-phase motor is also known as an induction start/induction run motor. It has two windings: a start and a main winding. The start winding is made with smaller gauge wire and fewer turns, relative to the main winding to create more resistance and less reactance, thus putting the start winding's field at a different angle than that of the main winding which causes the motor to start rotating. The main winding, which is of a heavier wire, keeps the motor running the rest of the time (figure 2.8).

Figure 2.8 Split-phase motor. a) Circuit b) Currents phase chart

In the figure 2.8(b), there are shown the relation between the currents when the motor starts. Start winding current is delayed 15 degrees regard to supply voltage; whereas high main winding current is delayed about 40 degrees regard to supply voltage. In other words, the start winding attains that one of the opposing rotating statoric magnetic field is greater than other and it provides a net starting torque to the motor [5].

Starting winding capacity is based only on intermittent work. If centrifugal switch is broken and cannot switch off, generally because the electrical contacts get stuck, the excessive heat produced by high resistance of starting winding, raise the stator temperature, causing eventually the burning of both windings. Most of split-phase motors have thermic relays, serial connected with supply terminal, with the aim to disconnect the motor from supply whenever the temperature is too high. [1].

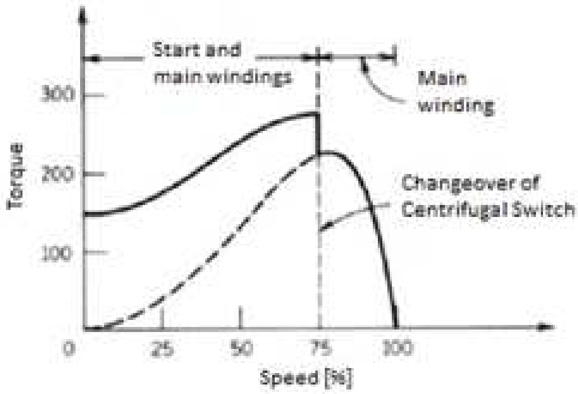

Figure 2.9 Split-phase motor. Torque-speed characteristic

The main disadvantage is the fact that the starting torque is low, typically 100% to 175% of the rated torque. The motor draws high starting current, approximately 700% to 1.000% of the rated current. The maximum generated torque ranges from 250% to 350% of the rated torque.

Another drawback is that the motor with a big load produces an elliptic or pulsating torque that causes the rotor make annoying noise. For these reasons, split-phase motors are use in household applications as for example, small grinders, small fans, oil burners, polishers, washing machines, dishwashers, compressors, small pumps and blowers and other low starting torque applications with power needs from 1/20 to 1/3 hp. Avoid using this type of motor in any applications requiring high on/off cycle rates or high torque.

The speed control of these motors is relatively complicated because synchronous speed of the statoric rotating field is determined by the frequency and number of poles developed in the stator winding. I notice that all speed changes must be carried out at upper level of the centrifugal switch working limit and therefore lower than the synchronous speed; getting a very limited range of speed control [1, 5].

2.4.2. Capacitor start motors

This is a modified split-phase motor to improve the low starting torque of the split-phase motors, with a capacitor in series with the start winding (figure 2.9 a) to provide an approximately 90 degrees difference between main and starting windings currents (figure 2.9 b), rising the starting torque near to the rated torque. The capacitor start motor also has a centrifugal switch which disconnects the start winding and the capacitor when the motor reaches about 75% of the rated speed.

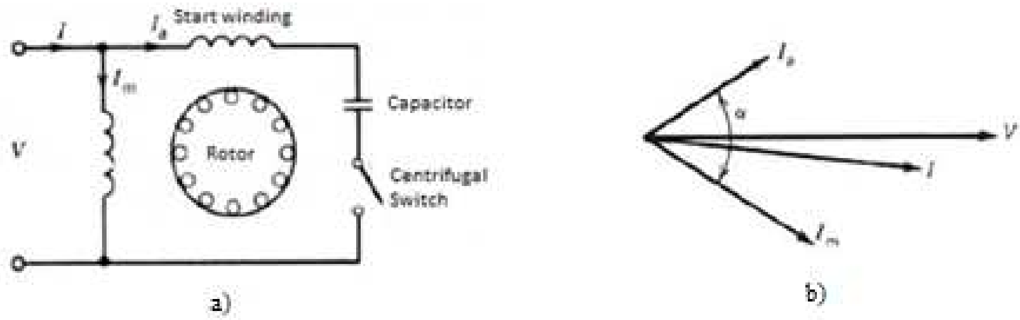

Figure 2.9 Capacitor start motor. a) Circuit b) Currents phase chart

The starting torque is typically 200% to 400% of the rated torque. And the starting current, usually 450% to 575% of the rated current, is much lower than the split-phase due to the larger wire in the start circuit. They are used in a wide range of belt-drive applications like small conveyors, large blowers, air conditioners, big washing machines and pumps; with power until 3/4 hp [1, 5]

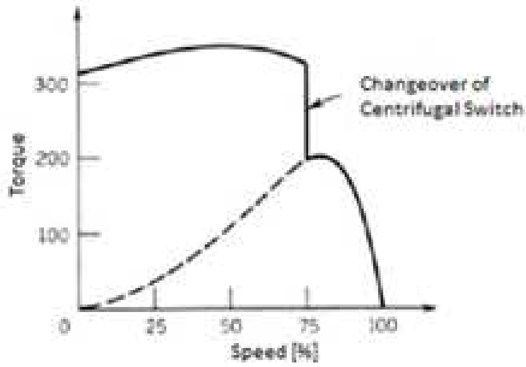

Figure 2.10 Capacitor start motor. Torque-speed characteristic

2.4.3. Permanent split capacitor motors (PSC)

Permanent split capacitor motor has two permanents windings, generally, these windings are equal, same gauge wire and same turns.

This motor has a run type capacitor permanently connected in series with the start winding (figure 2.11 a). There is no centrifugal switch which means that the main winding and start winding works all the time. Since the run capacitor must be designed for continuous use, it cannot provide the starting boost of a starting capacitor.

The typical starting torque of the PSC motor is low, from 30% to 150% of the rated torque, depending on rotor resistance. PSC motors have low starting current; usually less than 200% of the rated current, making them excellent for applications with high on/off cycle rates (figure 2.11 b).

The PSC motors have several advantages. The motor design can easily be altered for use with speed controllers. They can also be designed for optimum efficiency and High-Power Factor at the rated load. They are considered to be the most reliable of the single-phase motors, mainly because no centrifugal starting switch is required.

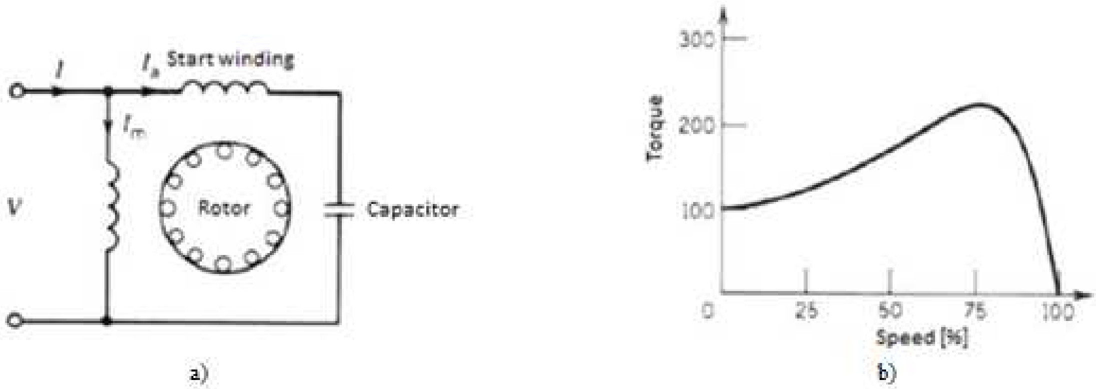

Figure 2.11 Permanent split capacitor motor. a) Circuit b) Torque-speed characteristic

Permanent split-capacitor motors have a wide variety of applications depending on the design. These include fans, air conditioners, blowers with low starting torque needs and intermittent cycling uses, such as adjusting mechanisms, gate operators and garage door openers. Of all the different types of single-phase AC induction motors, a permanent split capacitor motor makes the best choice for variable speed control [5, 7].

2.4.4. Capacitor start&run motors

This motor has a start type capacitor in series with the start winding like the capacitor start motor for high starting torque. Like a PSC motor, it also has a run type capacitor that is in series with the start winding after the start capacitor is switched out of the circuit (figure 2.12 a). This allows high starting torque (figure 2.12 b).

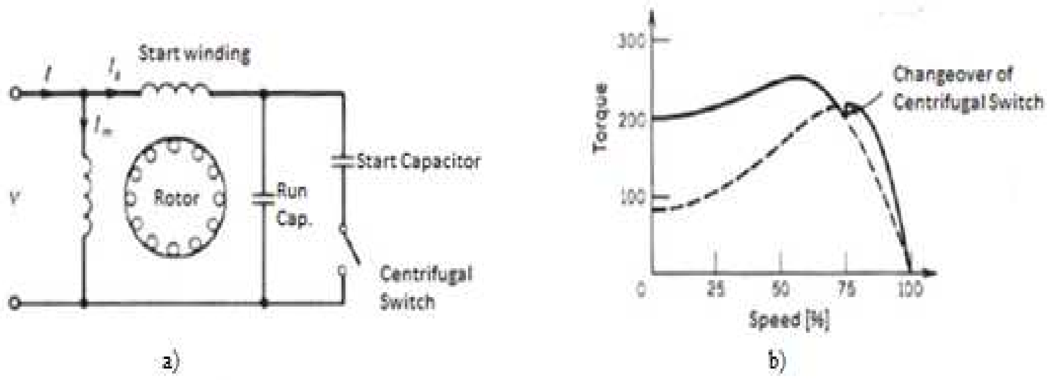

Figure 2.12 Capacitor start&run motor. a) Circuit b) Torque-speed characteristic

This type of motor combine the advantages of noiseless operation and limited speed control of PSC motor with high starting torque of the capacitor start motor. It can be designed for lower full-load currents and higher efficiency. This motor is costly due to start and run capacitors and centrifugal switch. It is able to handle applications too demanding for any other kind of single-phase motor. These include woodworking machinery, air compressors, high-pressure water pumps, vacuum pumps and other high torque applications requiring 1 to 10 hp [5]

2.4.5. Shaded-pole motors

All of the single-phase motors described above have stator with uniform air gaps with regard to its rotor and stator windings, which are placed equally around the stator. The starting methods of these motors are based on split-phase principle to provide a rotating magnetic field to start the motor to rotate. Shaded-pole motors do not use this theory.

Shaded-pole motors have only one main winding and no start winding. Starting is by means of a design that rings a continuous copper loop around a small portion of each of the motor poles (figure 2.13 a). This “shades” that portion of the pole, causing the magnetic field in the shaded area to lag behind the field in the unshaded area. The reaction of the two fields gets the shaft rotating.

Because the shaded-pole motor lacks a start winding, starting switch or capacitor, it is electrically simple and inexpensive. Also, the speed can be controlled simply by varying voltage, or through a multi-tap winding. Mechanically, the shaded-pole motor construction allows high-volume production. In fact, these are usually considered as “disposable” motors, meaning they are much cheaper to replace than to repair.

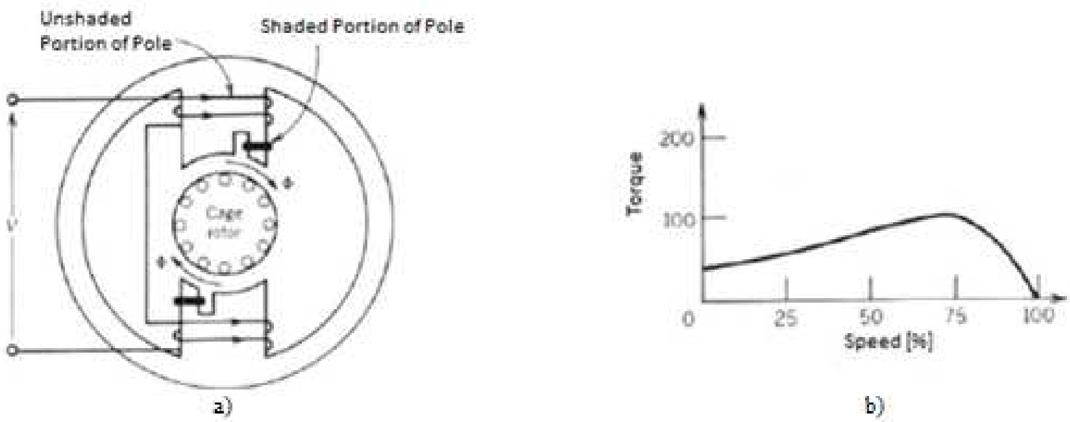

Figure 2.13 Shaded-pole motor. a) Circuit b) Torque-speed characteristic

Shaded-pole motor has many positive features but it also has several disadvantages. Its low starting torque is typically 25% to 75% of the rated torque (figure 2.13 b). It is a high slip motor with a running speed 7% to 10% below the synchronous speed. Generally, efficiency of this motor type is very low (less than 20%).

The low initial cost suits the shaded-pole motors to low horsepower or light duty applications. Its low starting torque limits its application to electric grills, movie projector, small bellows, vending machines and maybe their largest use is in multi-speed fans for household use. But the low torque, low efficiency and less sturdy mechanical features make shaded-pole motors impractical for most industrial or commercial use, where higher cycle rates or continuous duty are the standard [1,5].

2.5. Discussion

After I have checked all the features of each single-phase motor and also its advantages and drawbacks, I decide to use the Permanent Split Capacitor (PSC) motor because of these reasons:

1. It is the single-phase induction motor that makes the less noise.
2. Excellent for applications with high on/off cycle rates.
3. The most reliable of the single-phase motors.
4. The best choice for variable speed control.
5. It is the one that we had in the laboratory.

Therefore, we will discuss different techniques and drive topologies to control the speed of a PSC motor in one and two directions.

2.5.1. Characteristics of the motor

The selected motor is a PSC motor, made by ZAFFER and their characteristics are:

CHARACTERISTICS	MOTOR	UNITS
Power	220	W
Voltage	230	V
Frequency	50	Hz
Rated Current	1.05	A
Speed	17	Rpm
Class	F	
International Protection code	IP-44	

Figure 2.14 PSC motor used in the project

Chapter 3: Speed control for PSC induction motors

There are a lot of applications where it may be necessary to change the speed of the single-phase induction motor, for instance, in blowers, fans, household appliances, trains, etc. Then it is useful to know some techniques for varying single-phase induction motor speed. Two main techniques are used in this kind of motor: controlling the amplitude of the voltage source (slip control) or controlling the frequency and voltage of the supply (V/f control). It is possible to use the Vector Control, which is usually used in three-phase motors, but Vector Control techniques for the single-phase induction motors drives have not been widely developed because are very complex in spite of several advantages.

3.1. Voltage Control

The speed of an induction motor can be controlled by changing the effective amplitude of the stator voltage at constant frequency. According to the equation 2.4, next figure shows torque-speed characteristic for variable voltage.

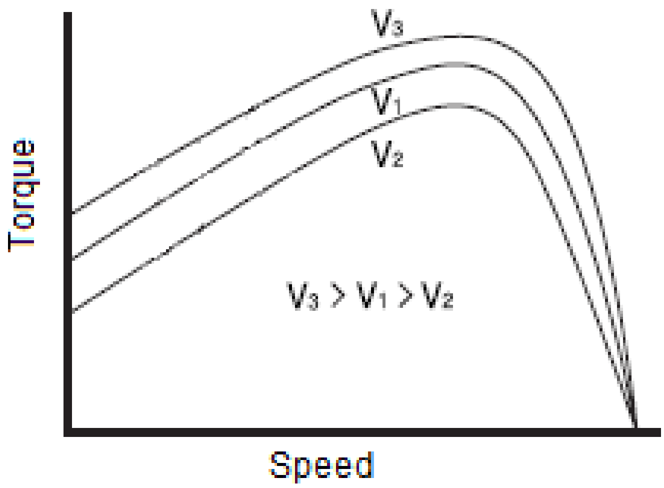

Figure 3.1 Torque-speed characteristic for variable voltage

This method is mostly used in fan or blower type motors with high slip. The speed control in this method operates by decreasing the air gap flux value, therefore increasing the slip, which means bad efficiency. The stator voltage can be controlled by two methods: integral cycle control and phase control [4, 7].

3.1.1. Integral Cycle Control

Integral Cycle Control is based on allowing certain number of complete cycles of the supply voltage to pass to the load. This can simply be done by turning on and off the source voltage. That is the reason why this technique is also called On-Off Control.

Burst Fire Control, Single Cycle Control and Advanced Single Cycle Control are three different ways used in this technique.

3.1.1.1. Burst Fire Control

The Burst Firing mode consists of firing complete cycles of supply to the load.

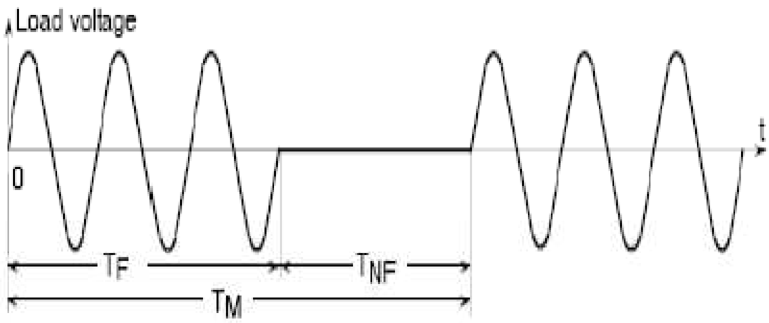

Figure 3.2 Burst Fire Control.

The load power is proportional to the ratio of the firing time (T_F) to the modulation time (T_M). The off time (T_{NF}) is also a series of whole supply cycles.

$$\boldsymbol{T_M = T_F + T_{NF}} \qquad (\mathbf{3.1})$$

The RMS value of the load voltage is:

$$\boldsymbol{V_{L(rms)} = V_{I(rms)}\sqrt{\frac{T_F}{T_M}}} \qquad (\mathbf{3.2})$$

Where:
$V_{I(rms)}$ = The effective of the supply voltage.

For burst firing mode, the firing time (T_F) is fixed to a certain time and the effective value of load voltage is changed by increasing or decreasing the off time (T_{NF}).

3.1.1.2. Single Cycle Control

3.1.1.2.1. Normal Single Cycle Control

The mode of firing with only one firing and one non-firing cycles is called the Single Cycle.

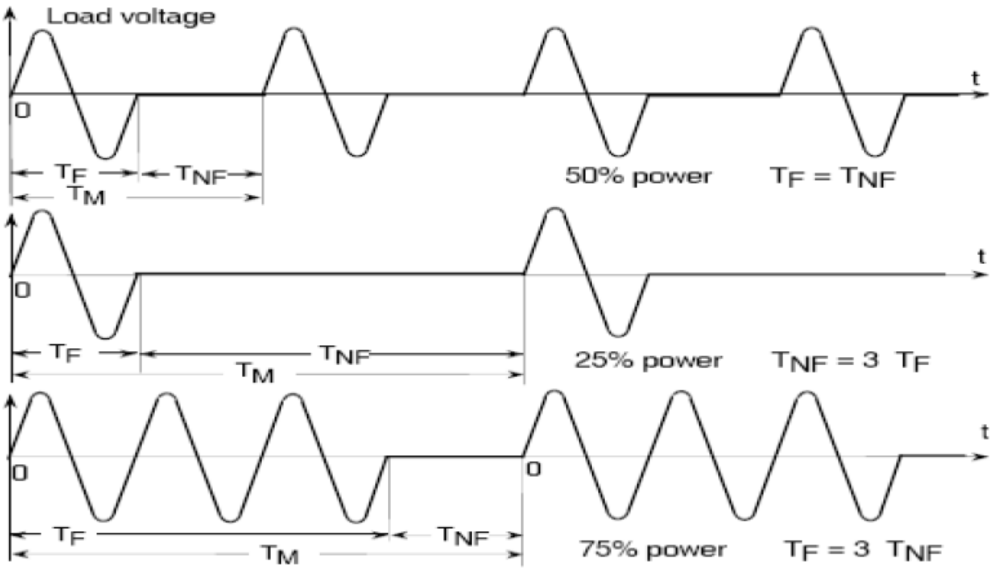

Figure 3.3 Load voltage waveform with normal single cycle control

At 50% of nominal power the firing is adjusted so that the firing time (T_F) and non-firing times (T_{NF}) are equal. For a set point less than 50% power the non-firing time is increased and for a set point of power greater than 50% the firing time is increased.

3.1.1.2.2. Advanced Single Cycle Control

To reduce the power fluctuations during the modulation period, Advanced Single Cycle firing can be implemented using half cycle for non-firing.

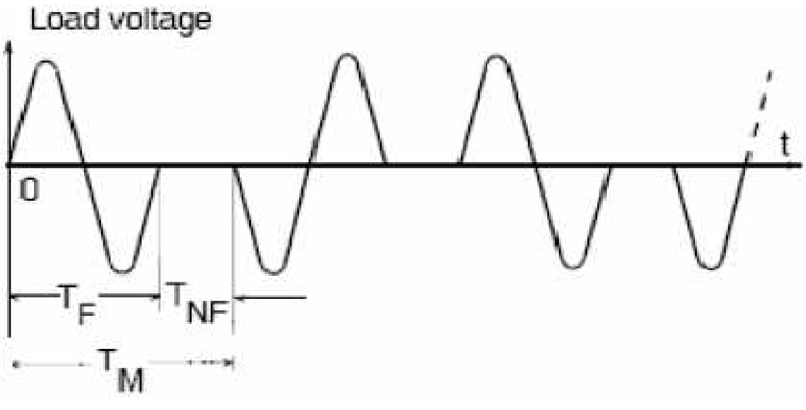

Figure 3.4 Load voltage waveform with advanced single cycle control.

The effective value for Normal Single Cycle and Advance Single Cycle methods are both the same as which was given in Burst Firing mode [4, 7]

3.1.2. Conduction angle control

Because of its very low cost and simplicity, the most popular technique of supplying PSC induction motors is the conduction angle control. To carry out this control, a TRIAC device is used.

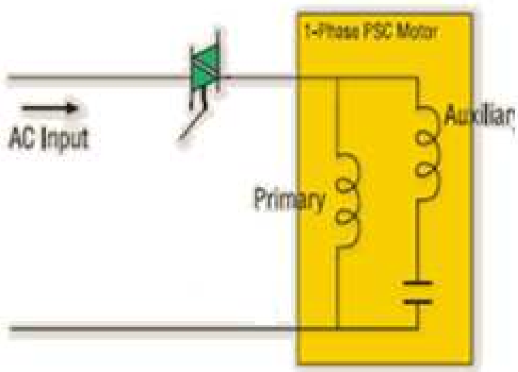

Figure 3.5 Conduction angle control circuit

The conduction angle is adjusted by changing the switching instant of the TRIAC device. In such a way, the conduction angle can be varied from 180° to 0°. The voltage RMS value is a function of the conduction angle [11].

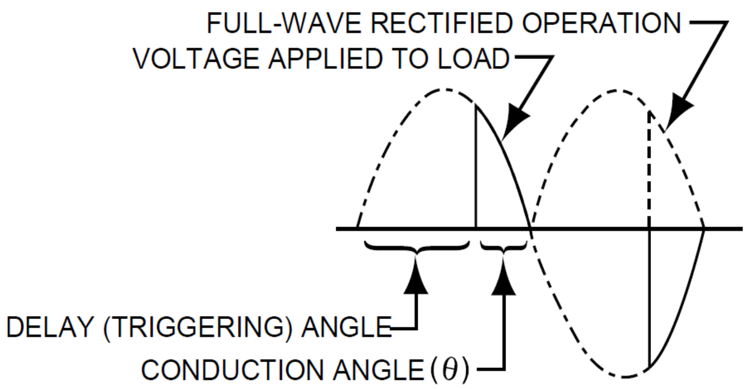

Figure 3.6 Explanation of the wave controlled by the conduction angle

3.2. Converter topology (V/f Control)

As it is in the three phase induction motor, the single phase induction machine also has variable speeds for different frequency values. The constant V/f technique can also be used for controlling the single phase induction motor.

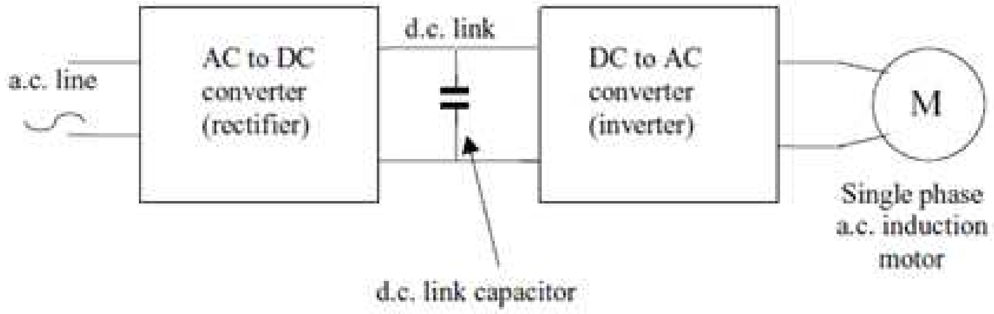

Figure 3.7 Converter topology

In a conventional converter, the AC supply voltage is converted into DC voltage using the diode bridge rectifier at the input. The DC voltage is then filtered by the filter capacitor in the DC link. Finally, the DC voltage is converted back to an AC voltage of the desired amplitude and frequency by the inverter. PWM modulation is used to generate an output voltage waveform.

By varying the frequency of supply to induction motor we can control the speed of the motor. But by varying only the frequency changes the flux which results in changes in torque. Furthermore, if the motor is fed with less frequency without changing the voltage, there are high magnetizing current in the motor, which means the motor temperature will increase and eventually the motor will burn out.

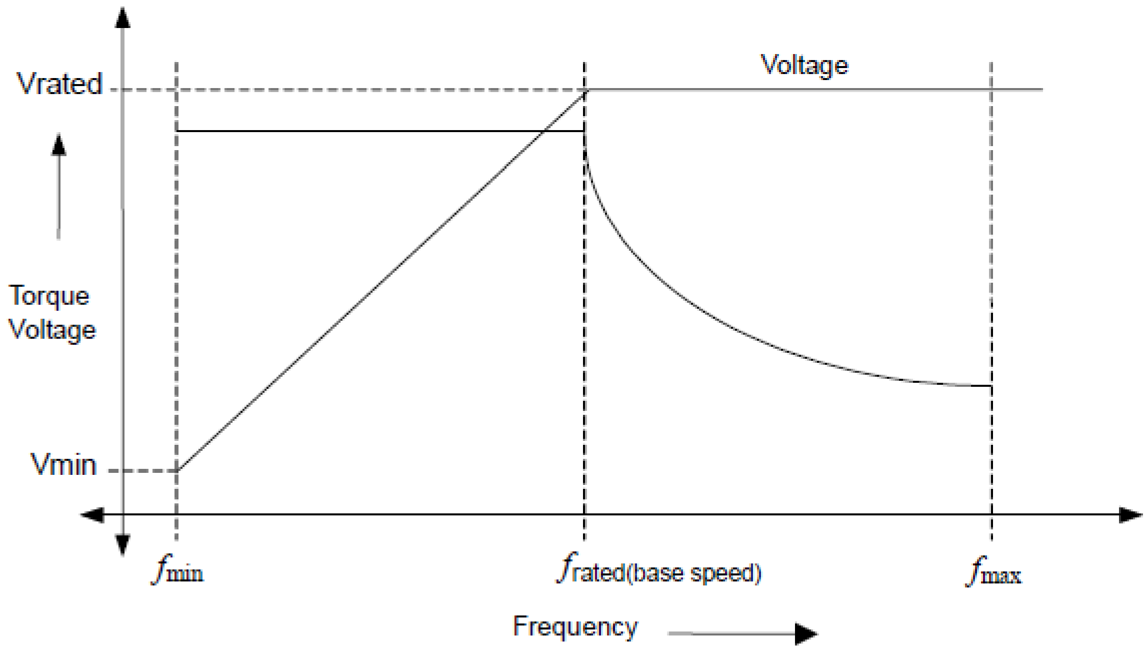

Figure 3.8 Voltage-torque-frequency characteristics with V/f control

In order to keep constant the torque and avoid high magnetizing current, the air gap flux must be constant which means that the voltage has to be proportional to the frequency. It can be seen from equation 2.4 that keeping the V/f ratio constant the air gap flux can be kept constant, the torque-speed characteristic is shown in figure 3.9.

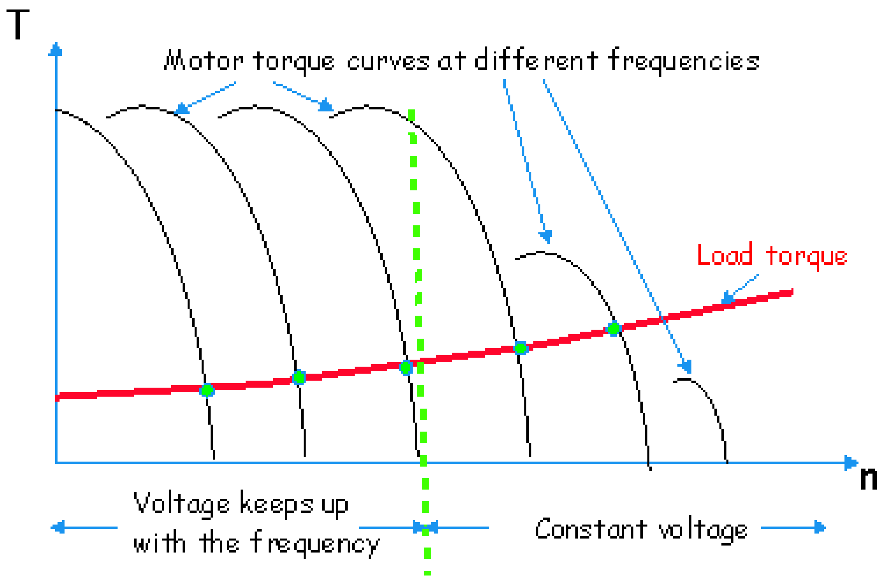

Figure 3.9 Torque-speed characteristic for V/f control

According with the equation 2.4 and a constant V/f ratio, the torque is always in the maximum, between no speed and synchronous speed. After that it can be possible to increase the frequency but not the voltage, because the motor windings would not support a voltage higher than its rated voltage. The maximum torque value is given by equation 2.4.

This topology has two big advantages: it has a good output (small slip) and a high starting torque. But this speed control technique has a disadvantage in low frequencies (low speed). In low frequency region, air gap flux is reduced due to the stator impedance drop. To overcome the effects of stator impedance, it is necessary to inject an auxiliary voltage V_{aux} so that the rated air gap flux and full torque can become available [3, 7, 11]

3.2.1. V/f Control

3.2.1.1. Unidirectional Control

V/f control in one direction makes the drive topology and control algorithm relatively easy. The task is to generate a variable voltage and frequency power supply from a fixed voltage and frequency power supply. The figure 3.10 shows the block diagram representation of this drive topology, with the three basic building sections discussed earlier.

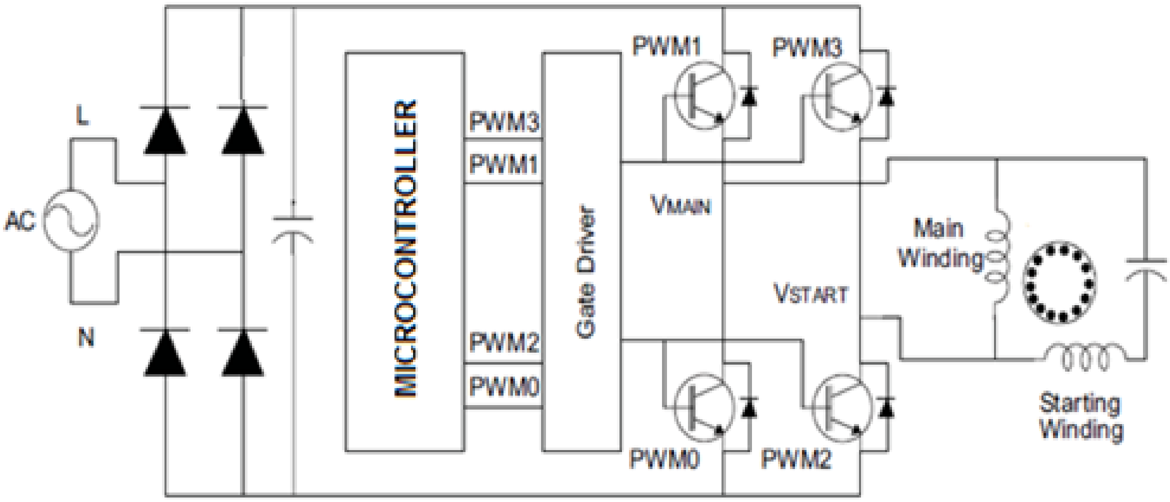

Figure 3.10 H-bridge for PSC motor with the capacitor

PWM modulation is used to create the signals to control the switches of the inverter. This PWM signals are generated by the microcontroller, which is capable of outputting up to three pairs of PWMs with dead band in between the pairs. Dead band is essential in an induction motor control application to avoid cross conduction of the DC bus through the power switches when one turns off and the other turns on [12].

3.2.1.2. Bidirectional Control

In this section, we will discuss two methods of bidirectional speed control for PSC motors using a microcontroller-based drive. The drive topologies discussed here produce voltages, which drive the main winding and start winding at 90 degrees phase shifts to each other. This allows remove the capacitor, which is in series with start winding, from the circuit permanently.

A) <u>H-Bridge Inverter</u>

This method has a voltage doubler on the input side; on the output side an H-bridge or two-phase inverter is used (figure 3.11). One end of the main and start windings are connected to each half bridge; the other ends are connected together at the neutral point of the AC power supply, which also serves as the center point for the voltage doubler.

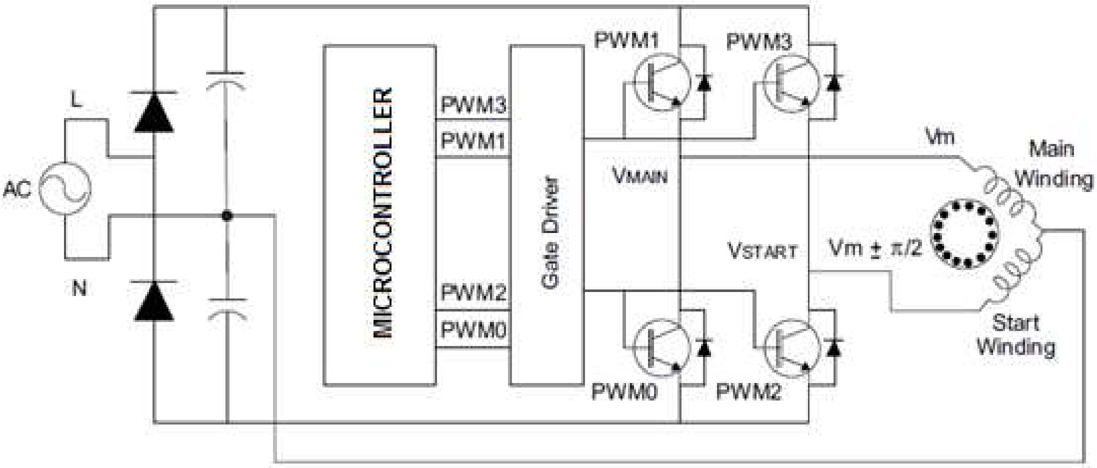

Figure 3.11 H-bridge for PSC motor without the capacitor

The control circuit requires four PWMs with two complementary pairs and sufficient dead band between the complementary outputs. PWM0-PWM1 and PWM2-PWM3 are the PWM pairs with dead band. Using PWMs, the DC bus is synthesized to provide two sinusoidal voltages at 90 degrees out of phase with varying amplitude and varying frequency, according to the V/f profile. If the voltage applied to the main winding lags the start winding by 90 degrees, then the motor runs in the forward direction. To reverse the direction of rotation, the voltage supplied to the main winding should lead the voltage supplied to the start winding. The figures 3.12 and 3.13 show the voltage applied to the main and the start winding, the first one in the reverse direction and the second one in the forward direction.

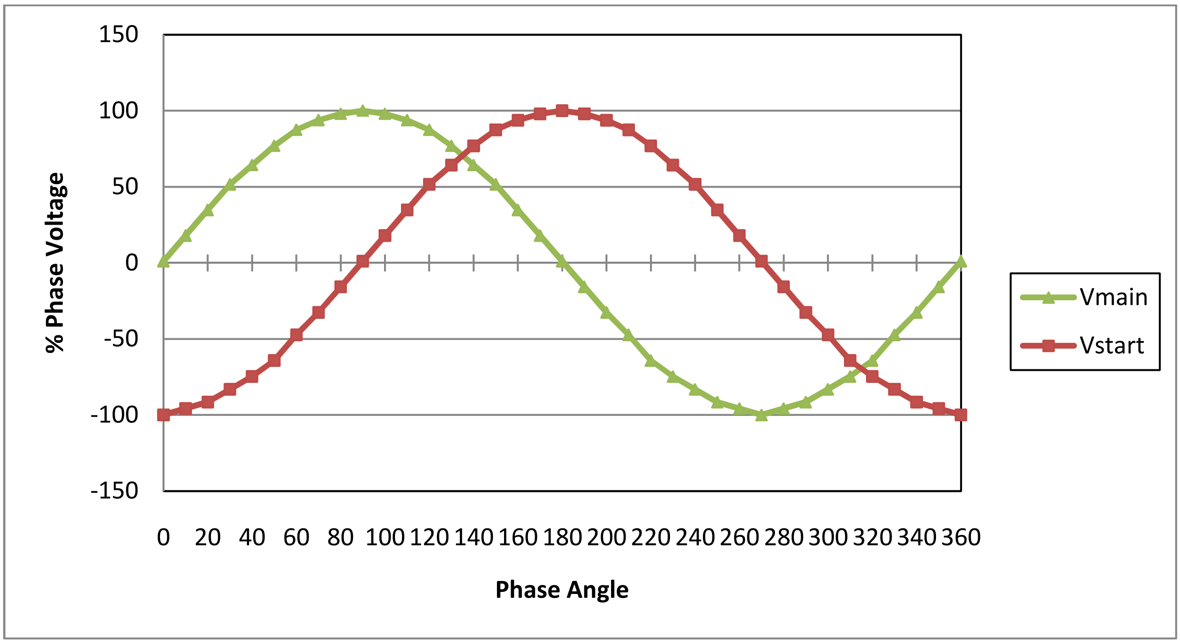

Figure 3.12 Motor running in reverse direction

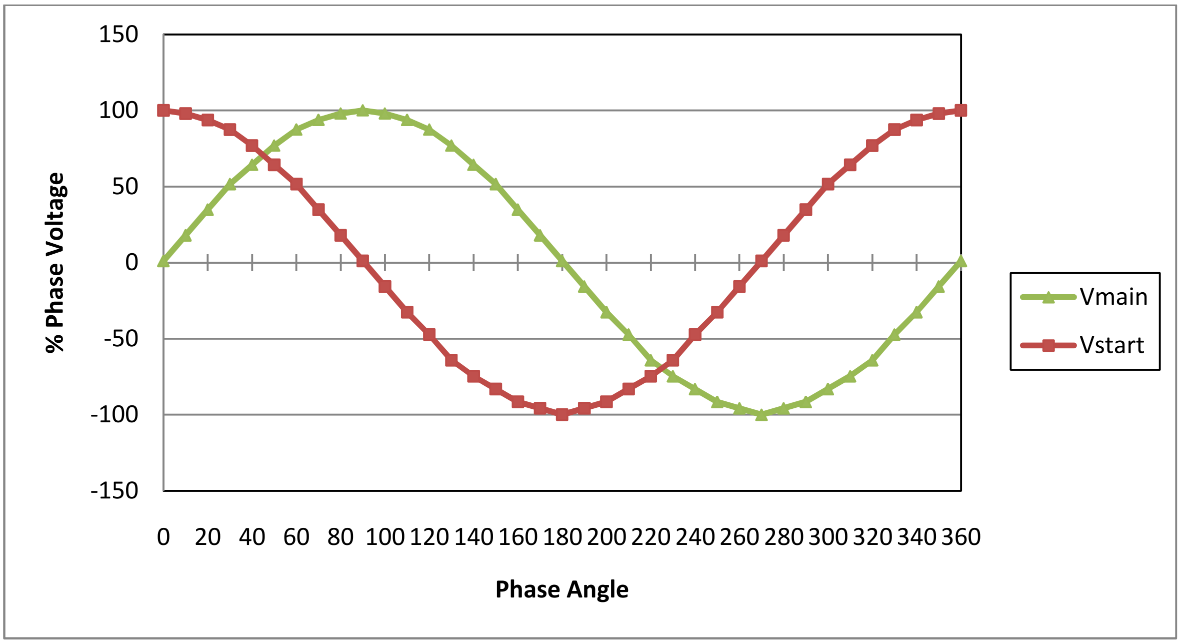

Figure 3.13 Motor running in forward direction

B) Three-Phase Bridge Inverter

The input section is replaced with a standard diode-bridge rectifier. The output section has a three-phase inverter bridge. The main difference from the previous scheme is the method used to connect the motor windings to the inverter. One end of the main and start windings are connected to one half-bridge each. The other ends are attached together and connected to the third half bridge.

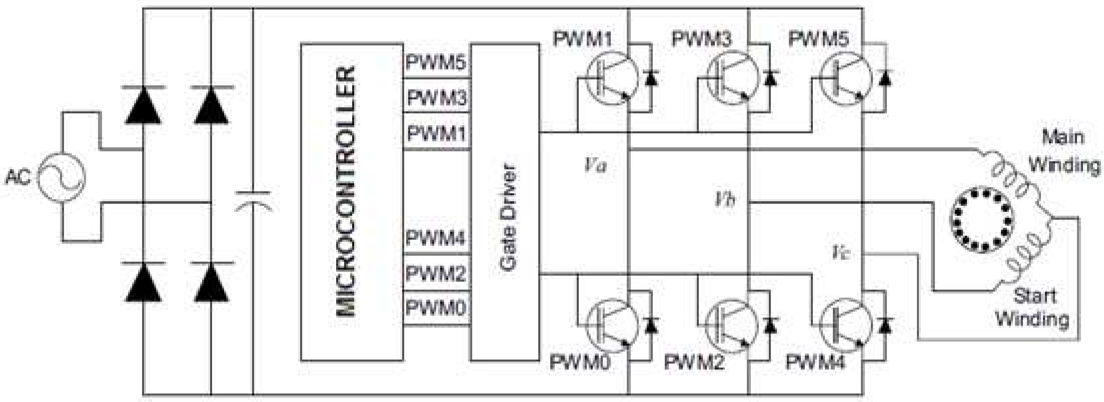

Figure 3.14 Three-phase inverter bridge

The winding voltages, V_a, V_b and V_c, should be controlled to achieve the phase difference between the effective voltages across the main and starting windings, in order to have a 90 degrees phase shift to each other [12].

3.3. Discussion

Each control technique has advantages and disadvantages which effect in the selection of the control method. The voltage control technique has a simple structure, is easy to control and is low cost. This technique is based on varying the slip rate. The increase in the slip rate causes the speed to decrease. A major drawback is the increasing stator currents which lead to more copper loss and machine heating.

It is necessary in motor drives to apply a continuous current to the motor in order to protect the motor from electromagnetic moment pulsations and speed oscillations. Motors having high inertia may be harmed from these oscillations.

The *integral cycle (On-Off) control* is based on supplying and cutting the supply currents, leading to discontinuities in the motor current which is a disadvantage in using this control method. This problem can be improved by increasing the total on and off time. One other effect of discontinuing currents in *integral cycle control* is that each control cycle the stator voltage is reduced to zero and again increased to the supply voltage value which increases the transient effects of the motor which is not desired.

In *phase control* the motor current is much more continuous compared to the *integral cycle control*, but still has discontinuity.

In *constant V/f control*, the motor currents are nearly pure sinusoidal with very small harmonics. This result brings an advantage to this control method compared with *phase* and *integral cycle control.*

The *integral cycle control* and *phase control* produce very high harmonic content in both motor and supply current waveforms. The effects of these are low efficiency of the drive and transmission lines, acoustic noise and electromagnetic interference. The high harmonic pollution does not comply with strict European EMI/EMC regulations.

As it was said above, the main advantage of *V/f control* topology is the ability to generate both the amplitude and frequency of the output voltage independently. Another advantage is the harmonic reduction, due to symmetric properties and how the switches are turned on and off; the harmonics are reduced at the output and provide a continuous current to the motor. This topology has one disadvantage; it is the higher cost than the voltage control topologies. It requires numerous active and passive components.

Most PSC motors are designed to run in one direction. However, many applications call for bidirectional motor rotation, as our application. Gear mechanisms or external relays and switches were used to achieve bidirectional rotation. When mechanical gears are used, the motor shaft runs in one direction and the gears for forward and reverse engage and disengage according to the direction required. Using a microcontroller-based system, you can control the speed but also the direction of rotation can be also changed, based on an algorithm. In addition, there is another disadvantage because the increased capacitor reactance at low frequency tends to drastically reduce the influence of the start winding. Therefore, the pulsation torque increases once the frequency drops, leading to vibrations and higher audible noise.

Using a microcontroller is possible to generate 90 degrees phase between main and start windings, which means that the big capacitor can be removed, thus reducing the total system cost.

About bidirectional control, there are two methods: *H-bridge* or *Three-phase bridge*. The *H-bridge* is a good V/f control but it has following disadvantages:

- The common point of the windings is directly connected to the neutral power supply. This may increase the switching signals creeping into the main power supply and may increase the noise. In turn, this may limit the EMI level of the product, violating certain design goals and regulations.
- The effective DC voltage handled is relatively high due to the input-voltage doubler circuit. Moreover, the cost of the voltage doubler circuit itself is high due to two large power capacitors.

A better solution to minimize these problems would be to use a t*hree-phase bridge inverter*. With this technique the control becomes more efficient, but the control algorithm becomes more complex. In addition, all devices have the same voltage-stress level, which means longer service life.

Afterward, we discussed different methods of speed control that can be used with a PSC motor. Our final conclusion is that controlling using a *three-phase inverter* topology provides the best results, such as power efficiency, longer life, lower power dissipation, lower EMI level, reduced audible noise, better control over the application and lower overall system cost [3, 4, 7, 11, 12].

Chapter 4: Design

4.1. Three-Phase Bridge Inverter

The three-phase bridge inverter consists of: the rectifier with the filter, the control circuit and the inverter. In the input the diode bridge rectifier convert the AC supply voltage into DC voltage and then is filtered by the capacitor. According to the V/f profile, the control circuit by means of PWM modulation; manage the switches of the inverter, where the DC voltage is converted back to an AC voltage of the desired amplitude and frequency by the inverter.

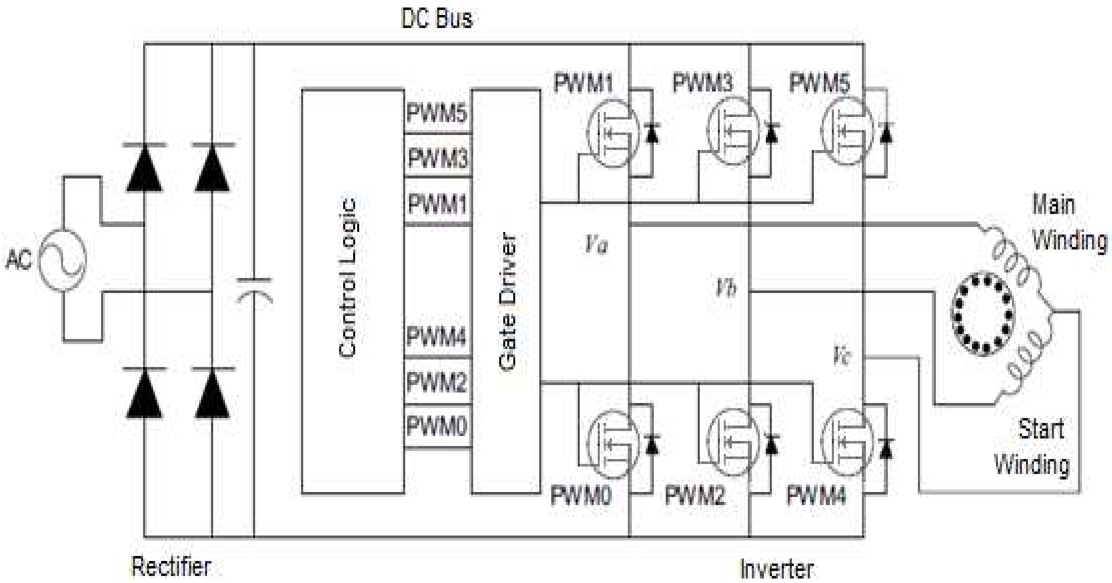

Figure 4.1 Three-phase inverter bridge

In this topology, one end of the main and start windings are connected to one half-bridge each. The other ends are attached together and connected to the third half bridge.

The winding voltages: V_a, V_b and V_c, are controlled to achieve the phase difference between the effective voltages across the main and starting windings to have a 90 degrees phase shift to each other.

In order to have equal voltage stress levels on all devices, which improves the device utilization and provides the maximum possible output voltage for a given DC bus voltage, all three-phase inverter voltages are kept at the same amplitude, as given by:

$$|V_a| = |V_b| = |V_c| \qquad (4.1)$$

The effective voltage across the main and start windings as given by:

$$V_{main} = V_a - V_c \qquad (4.2)$$
$$V_{start} = V_b - V_c \qquad (4.3)$$

If the voltage space vectors are used, the relation of these voltages can be shown in figure 4.2, where the length of a vector stands for the magnitude and the angle of the vector is the phase angle. In figure 4.2, the length of the vector is equal to half of the DC voltage. In order to fully utilize the DC voltage, voltage V_b is just the inverse of V_a and V_c has a certain angle (±90 degrees) from V_a and V_b, such that to control the revolving direction of the motor. The equations of the voltages are express in 4.4, 4.5 and 4.6.

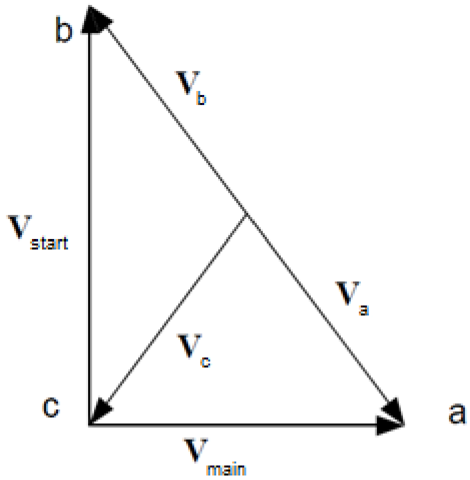

Figure 4.2 Voltage relation represented by space vectors.

$$V_a = \frac{V_{dc}}{2}\cos(\omega t) \qquad (4.4)$$
$$V_b = -\frac{V_{dc}}{2}\cos(\omega t) \qquad (4.5)$$
$$V_c = \frac{V_{dc}}{2}\cos(\omega t \pm 90°) \qquad (4.6)$$

The figures 4.3 and 4.4 show the phase voltages V_a, V_b and V_c and the voltages across the main winding (V_{main}) and starting winding (V_{start}) for forward direction.

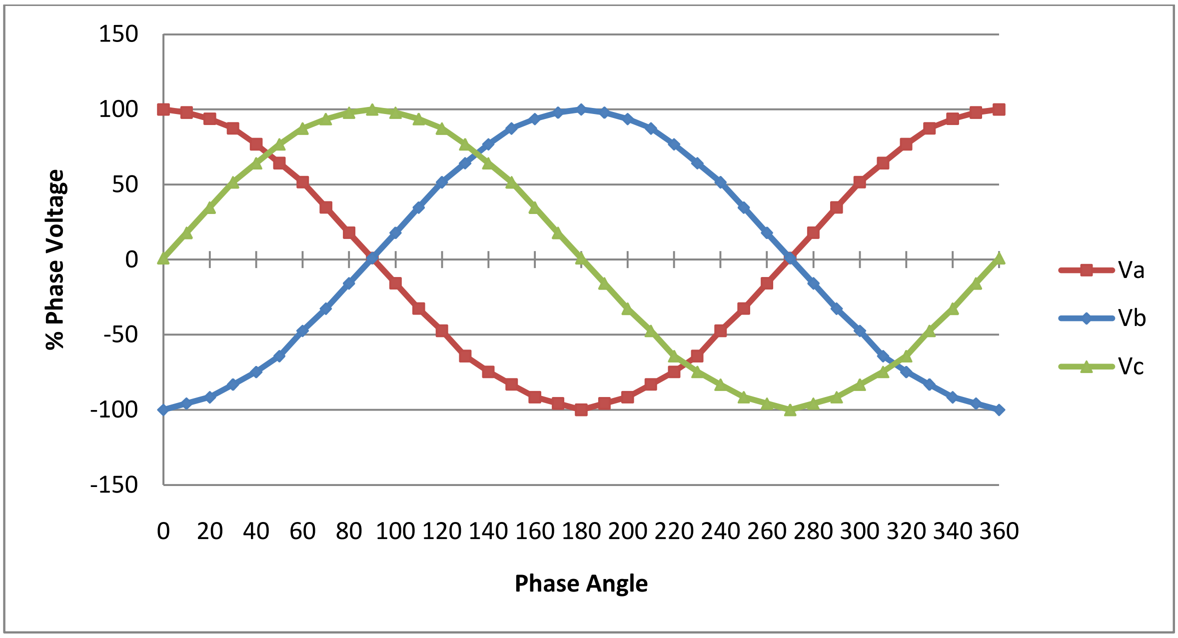

Figure 4.3 Phase voltages V_a, V_b and V_c.

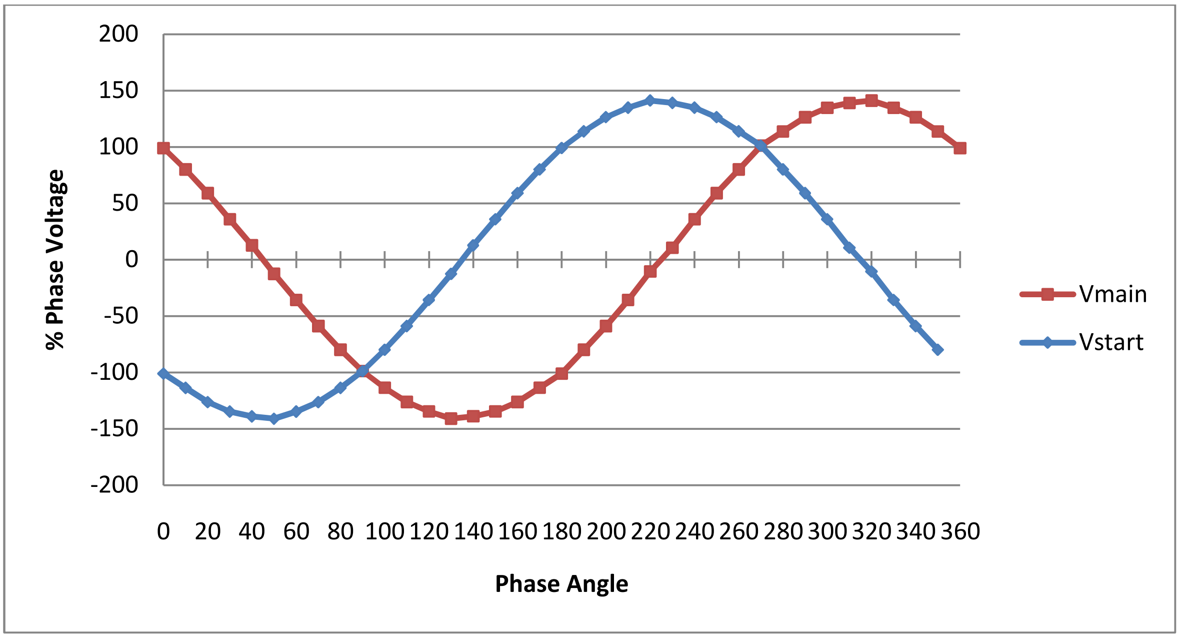

Figure 4.4 Voltage across the main winding and start winding.

The direction of rotation can be easily controlled by the V_c phase angle (±90 degrees) with respect to Va and Vb. The figures 4.5 and 4.6 show the phase voltages V_a, V_b and V_c and the voltages across the main winding (V_{main}) and starting winding (V_{start}) for reverse direction [13].

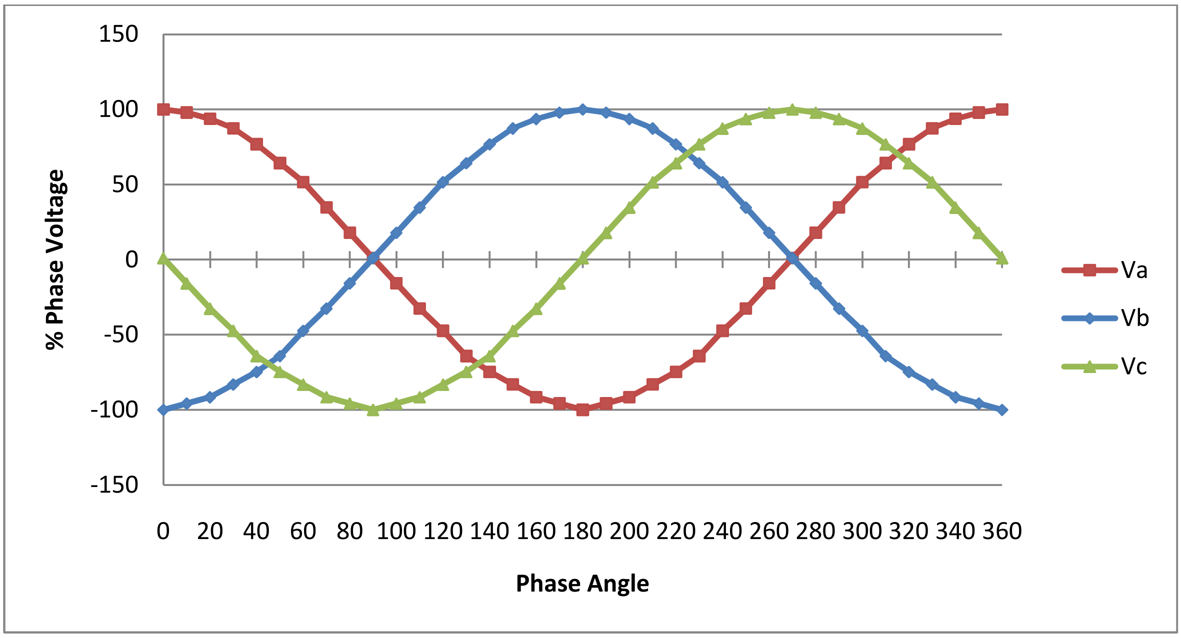

Figure 4.5 Phase voltages V_a, V_b and V_c.

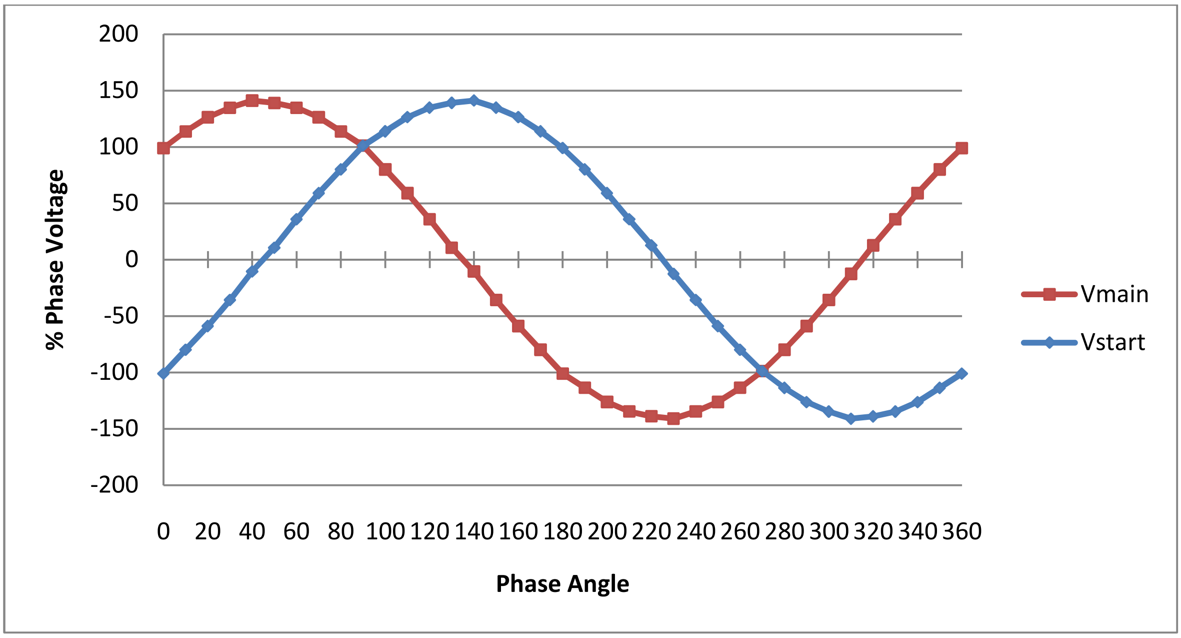

Figure 4.6 Voltage across the main winding and start winding.

4.2. Power Converters

As you can see from the diagram in figure 4.1, the power converters are the main modules in a three-phase bridge inverter. Power control or electric power fitting-out, is required converting it from one form to another and the switching characteristics power devices allow these conversions. Power converters make these functions and they are basically classified into five types:

1. AC-DC converters (Diode rectifiers and controlled rectifiers)
2. AC-AC converters (AC voltage controllers)
3. DC-DC converters (DC converters)
4. DC-AC converters (Inverters)
5. Static switches

According to the application and our circuit, it is necessary a rectifier and an inverter [6].

Chapter 5: Power Rectifier

A rectifier is a power converter that must produce a DC output voltage with a minimum content of harmonics. At the same time it must keep input current as sinusoidal as possible and in-phase with the input voltage, in order to keep the power factor close to 1. The quality of power processing of a rectifier requires knowing the content of harmonic in the input current, voltage and output current.

Rectifiers depending on the nature of the input supply are classified as detailed below:

1. Single-phase
    - Half-wave.
    - Full-wave Bridge.
2. Three-phase
    - Full-wave Bridge.

The converter required in this project according to the domestic application is a single-phase diode rectifier full wave bridge [2, 6, 7].

5.1.1. Single-Phase Rectifier

The most used technique in single-phase rectifier is the full-wave bridge shown in figure 5.1. It consists in four diodes in a full-bridge configuration called Graetz bridge.

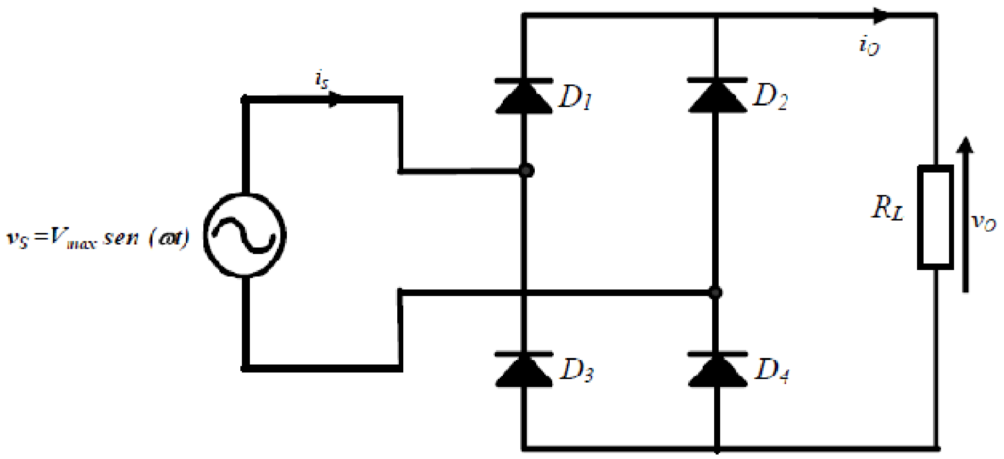

Figure 5.1 Single-phase rectifier

Always two diodes are conducting simultaneously. If the input voltage of the rectifier is positive (hemicycle positive), D1 and D4 conduct while D2 and D3 are reverse biased and therefore are blocked (off). Otherwise the voltage is negative (hemicycle negative), D2 and D3 conduct. In general, to know which diode can conduct is necessary to analyze which of the four diodes has higher voltage in its anode and which one has less voltage on its cathode. Figure 5.2 shows full-bridge rectifier waves with resistive load.

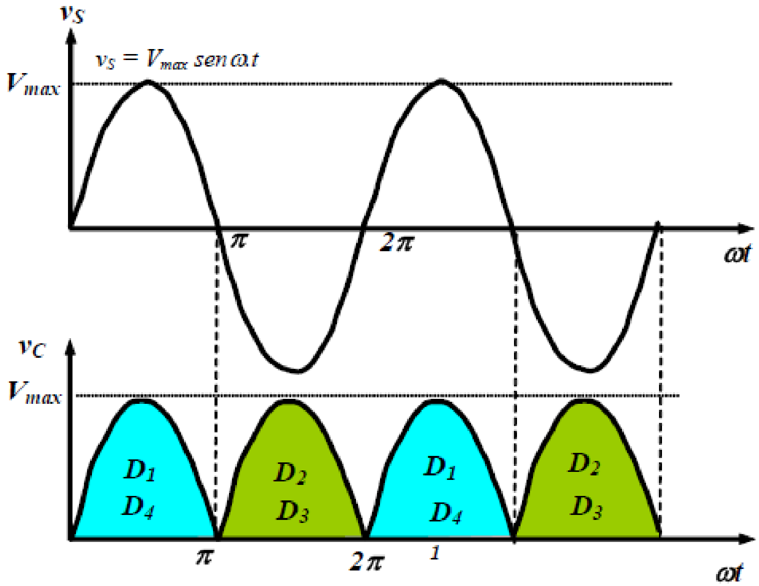

Figure 5.2 Load voltage waveform of single-phase rectifier.

The average and root-mean-square output voltages of an ideal single phase full-wave rectifier can be calculated as:

Average output voltage:

$$V_{Odc} = \frac{2}{T}\int_0^{\frac{T}{2}} V_{max}\ \sin\omega t\, d\omega t = \frac{V_{max}}{\pi}[-\cos\omega t]_0^{\pi} = \frac{2V_{max}}{\pi} = \frac{2\sqrt{2}\cdot V_{AC(rms)}}{\pi} \qquad (5.1)$$

Where:
V_p = the peak value of the supply voltage, 325V.
$V_{AC(rms)}$ = the rms value of the supply voltage: 230V.

Root-mean-square (rms) output voltage:

$$V_{Orms} = \sqrt{\frac{2}{T}\int_0^{\frac{T}{2}} (V_p\ \sin\omega t)^2 d\omega t} = \frac{V_p}{\sqrt{2}} \qquad (5.2)$$

Where:
V_p = the peak value of the supply voltage, 325V.

The current is always positive or zero, because if not the diodes would be blocked. Thus the power always goes to the load, never to the source, which means the rectifier is not reversible [7].

5.1.2. Choice of Single-Phase Rectifier

The choice of the single-phase rectifier is mainly based on the maximum current supported by the device. The motor current at startup is 1,05A. It was chosen the compact bridge rectifier KBL405G of MULTICOMP, which supports up to 4A, encapsulated and provides efficiency and reliability of operation. It is designed for general purpose and instrumentation applications. The main features are shown in table 5.1 and figure 5.3 [14].

Table 5.1 Bridge rectifier main features.

TYPE NUMBER	SYMBOL	KBL405G	UNITS
Maximum Recurrent Peak Reverse Voltage	V_{RRM}	600	V
Maximum RMS Voltage	V_{RMS}	420	V
Maximum DC Blocking Voltage	V_{DC}	600	V
Maximum Average Forward Rectified Current at T_A=50ºC	$I_{(AV)}$	4.0	A
Peak Forward Surge Current	I_{FSM}	150	A
Operating Temperature Range	T_j	-55 to +150	ºC

5.1.3. Bridge Rectifier Features

- Glass passivated junction.
- Ideal for printed circuit board.
- Reliable low cost construction.
- High surge current capability.
- High temperature soldering guaranteed.

Figure 5.3 Bridge rectifier KBL405G

5.1.4. DC Bus Filter Capacitor

The output voltage waveform after being rectified is that shown in figure 5.4, this voltage is not continuous and therefore the average output voltage is lower, consequently it is necessary to filter, minimizing the waveforms ripple and increasing the average voltage at the output [15].

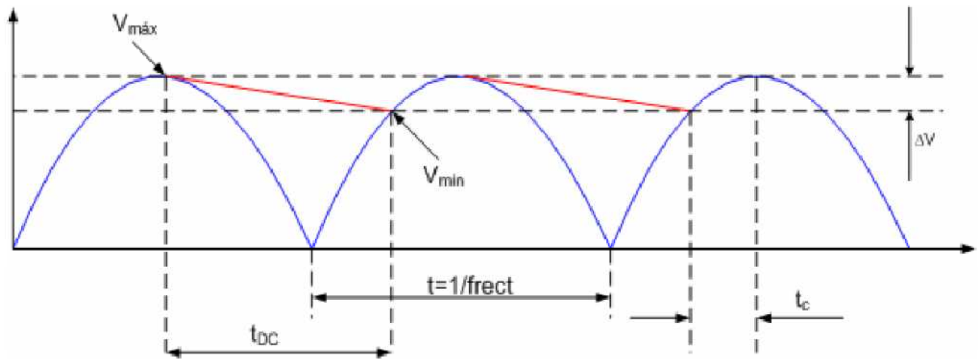

Figure 5.4 Rectified AC waveform showing conduction period from V_{min} to V_{max}

An electrolytic capacitor is used to smooth the rectified AC voltage from the bridge rectifier. Its capacitance is an inverse function of the allowed ripple voltage DV and can be derived from equation 4.9.

$$C_{min} = \frac{2P_{in}}{(V_{max}^2 - V_{min}^2) f_{rect}} \qquad (5.3)$$

Where:
P_{in} = the load power in watts.
V_{max} = the maximum value of the DC voltage.
V_{min} = the minimum value of the DC voltage.
f_{rect} = the frequency of the rectified voltage.

It should be noted that electrolytic capacitors lose some capacitance over time and that the tolerance of the initial capacitance value should also be considered at the time of selection [15].

For this design we have the following data:

$$V_{max} = V_{line} \cdot \sqrt{2} = 230 \cdot \sqrt{2} = 325.27\, V$$

$$V_{min} = 309\, V$$

$$P_{in} = 230\, W\text{ , motor power.}$$

$$f_{rect} = f_{line} \cdot 2 = 50 \cdot 2 = 100\, Hz$$

Where 2 is the number of pulses per cycle.

Substituting these values in the equation 5.3 we have:

$$C_{min} = \frac{2P_{in}}{(V_{max}^2 - V_{min}^2)f_{rect}} = \frac{2 \cdot 230}{(325.27^2 - 309^2)100} = 445.75\ \mu F$$

According to the above calculation, it should be placed at least one capacitance 445.75 µF. In this design we used a capacitance of 470µF in the DC bus directly as shown in figure 5.5.

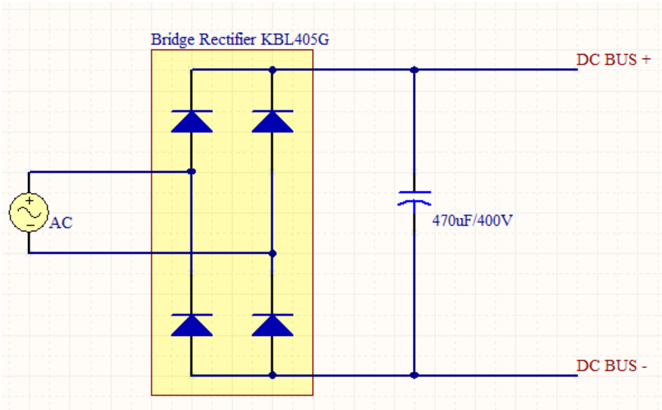

Figure 5.5 DC voltage source for the inverter

The voltage source that feeds the inverter is shown in figure 5.5. This figure shows how the connection of the bridge rectifier and DC Bus capacitor is.

Chapter 6: Power Inverter

The role of an inverter is change a DC input voltage to a symmetrical AC output voltage with the magnitude and frequency desired. Both the voltage and frequency can be fixed or variables. If you change the DC input voltage and the inverter gain remains constant, it is possible to obtain a variable output voltage.

On the other hand, if the DC input voltage is fixed and is not controllable, it is possible to obtain a variable output voltage if we vary the gain of the inverter, controlling it by the pulse width modulation (PWM) technique. The gain of the inverter can be defined as the relation between the AC output voltage and DC input voltage.

Inverters are used in AC motor drives and uninterruptible power supplies (UPS) where the objective is to produce a AC sinusoidal output wave whose magnitude and frequency can be controlled.

Inverters can be classified basically into two types:

- Single-phase inverters
- Three-phase inverters

And these in turn can be divided into Voltage Source Inverter (VSI) and Current Source Inverters (CSI).

VSI's are fed by a low impedance DC source such as a battery or a rectifier, with an output filter. The capacitive filter in parallel with the terminals of the inverter maintains constant the DC voltage. Therefore, this inverter is a voltage source adjustable in frequency in which the output voltage is essentially independent of load current.

In contrast, the Current Source Inverter is powered by a controlled current from a high impedance DC source. Typically a thyristor controlled rectifier feeds the inverter with regulated current through an inductor in series; therefore, the load current is controlled and the output voltage of the inverter is dependent on the load impedance.

Single and three phase bridge inverters PWM modulated will include below, where the type will be the Voltage Source, since those are useful to obtain the optimal constant V/f speed control of an induction motor [2, 6, 7].

6.1. PWM modulated inverters

6.1.1. Single-phase full bridge PWM modulated inverter

A single-phase full bridge inverter (figure 6.1) delivered a square wave of V_d amplitude as output voltage by switching transistors in diagonal pairs; however, if we introduce a 120 degrees phase shift switching each leg as shown in figure 6.2, the output voltage V_{AB} (equal to V_{A0}-V_{B0}) is almost a square wave with intervals of zero voltage of 120 degrees duration in each half cycle.

These intervals correspond to the times when terminals A and B are simultaneously connected to the DC supply and the load current flows through the transistor and freewheeling diode [7].

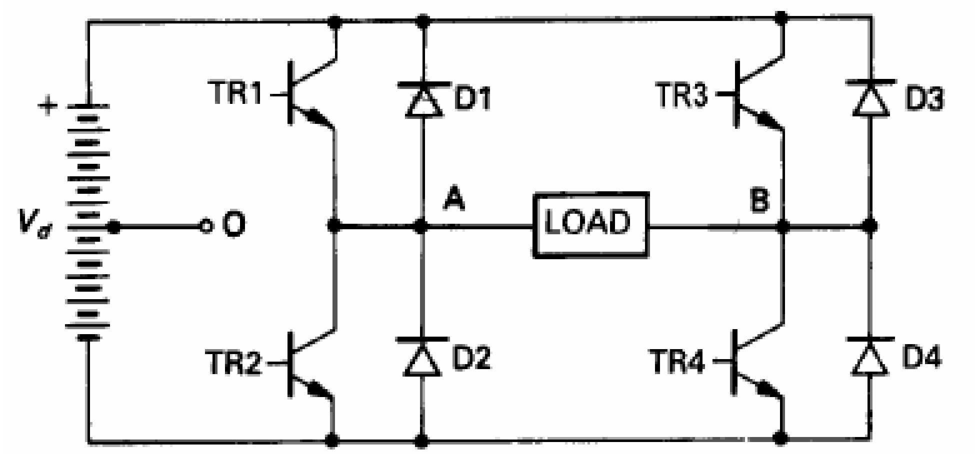

Figure 6.1 Single-phase bridge inverter

Table 6.1 Relation between turn-on switches and output voltage

TURNED ON SWITCHES	V_{AB} (OUTPUT VOLTAGE)
TR1 and TR4	V_d
TR1 and TR3	0
TR2 and TR3	$-V_d$
TR2 and TR4	0

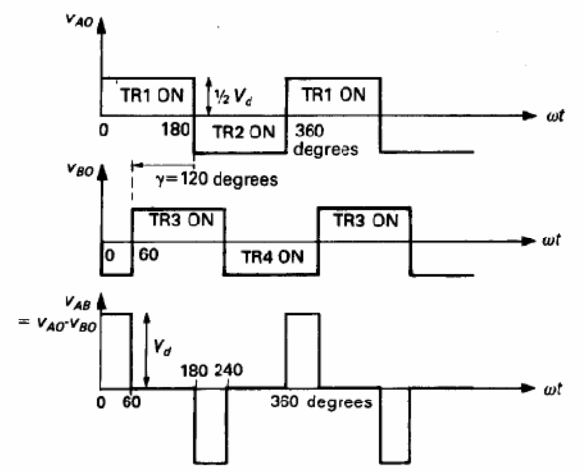

Figure 6.2 Output waveform from single-phase bridge inverter

The importance of this technique is that the fundamental output voltage can be varied from maximum to zero by moving the driving angles of TR3 and TR4 from zero to 180 degrees. This general method is called voltage control by Pulse Width Modulation (PWM) and particularly this technique is called modulation width of one pulse per half period.

In general, the process of PWM modifies the content of harmonics of the output voltage and can be used to minimize undesirable effects of harmonics on the load [7].

6.1.2. Square PWM and three-phase bridge inverter

An alternative type of PWM, known as modulation width of several pulse per half period or PWM square wave, involves obtaining a series of equal width pulses in each half cycle, as seen in figure 6.3. This is carried out by switching half bridge with the fundamental required frequency and the other half bridge with a multiple thereof. The duty cycle of the PWM wave is:

$$\boldsymbol{Duty\ cycle = \frac{T_1}{(T_1 + T_2)}} \qquad (\mathbf{6.1})$$

And the magnitude of the fundamental output voltage is controlled to vary it. A reduced output voltage gives a lower harmonic content by this technique [7].

For this purpose, control circuits are required; where a triangular carrier wave is compared with a reference square wave with the output frequency desired. These waves are shown in figure 6.3 for a leg of the inverter and the switching times of the transistors are determined by the intersections of the two waves.

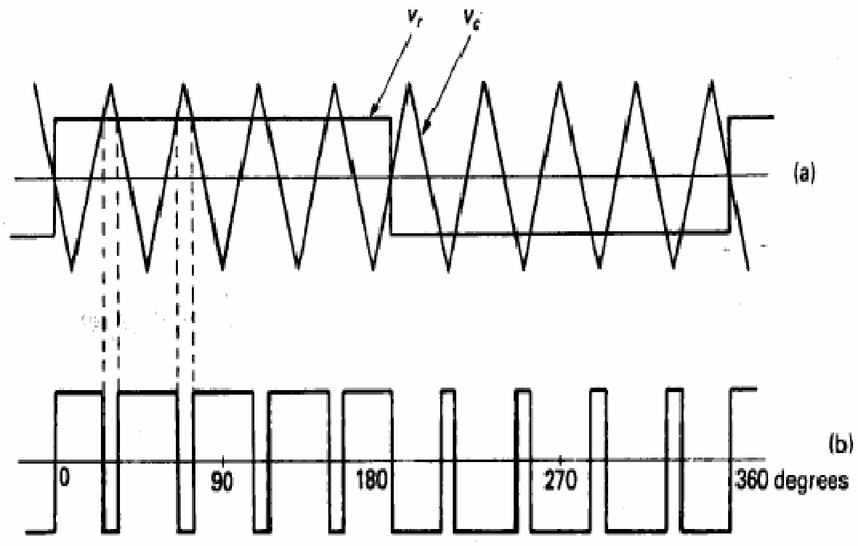

Figure 6.3 Output waveform from square PWM inverter. (a) Comparator input voltages. (b) Comparator output voltage and pole voltage.

When the reference voltage V_r (square wave) exceeds the carrier voltage V_c, the comparator output is high and the upper transistor is turned on. When V_r is less than V_c, the comparator output is low and the lower transistor is turned on. The output voltage of the comparator is a PWM signal, as shown in figure 6.3 b. The number of pulses per half cycle (p) is determined by the relation between the carrier and the reference frequency. For figure 6.3 b, p has a value of nine.

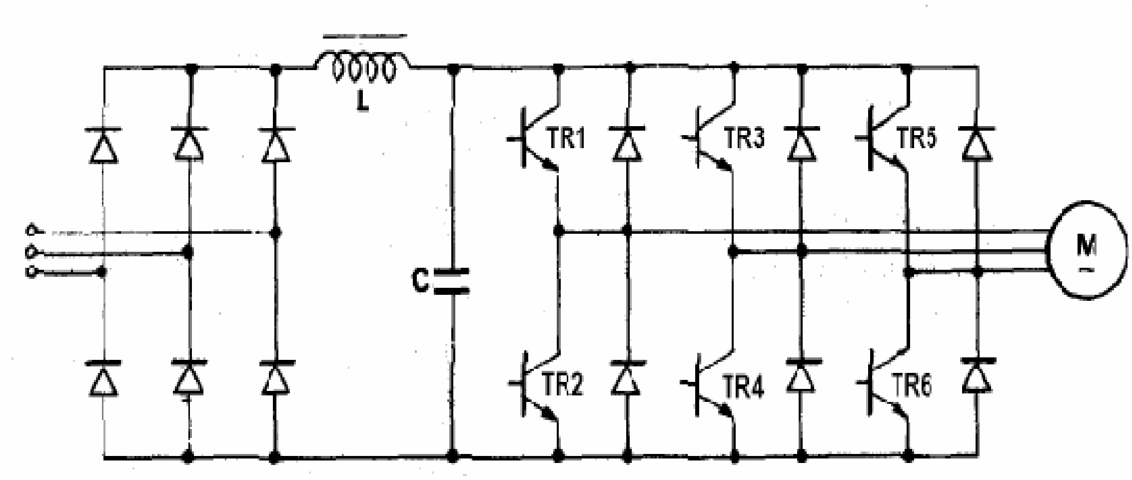

Figure 6.4 Three-phase bridge inverter

In a three-phase inverter (figure 6.4) each half cycle has a separate comparator, which is fed by the same triangular carrier wave. However, the three reference square waves are with 120° shift between each other, forming a three-phase balanced system.

If the relation with the carrier is a multiple of three, the triangular wave has an identical phase relation with each of the three modulated square waves, which is reflected in the voltage of each leg of the inverter. Figure 6.5 shows the reference square waves for phases A, B and C and the common triangular carrier to them. The voltages V_{A0}, V_{B0} and V_{C0} are also shown [7].

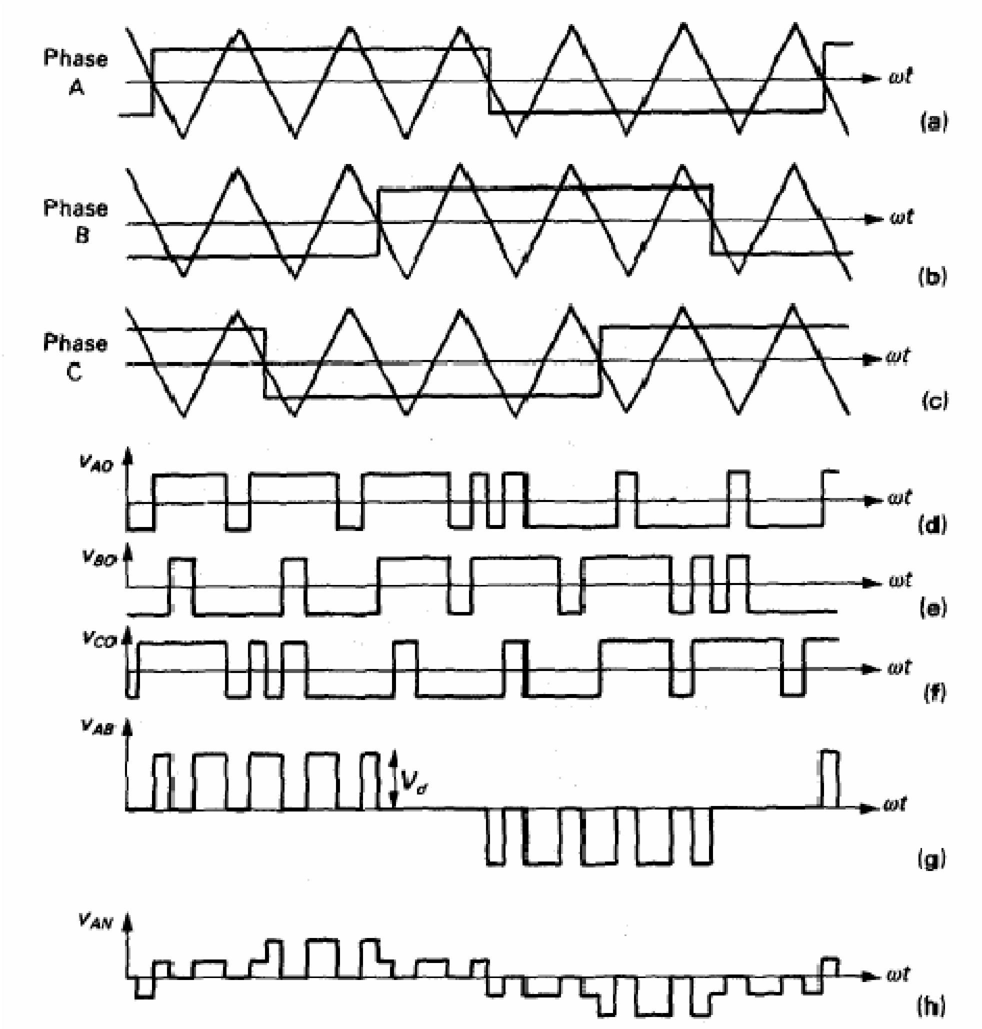

Figure 6.5 Output voltages from three-phase inverter controlled by squared PWM. (a), (b), (c) Comparator input voltages; (d), (e), (f) pole voltages; (g) line voltage; (h) line-neutral voltage

As usual, the line voltage $V_{AB}=V_{A0}-V_{B0}$, giving a series of equal width pulses evenly spaced, they are of the same amplitude V_d in each half cycle and with a half-width pulse at the ends. The modulation index (M) is defined as the ratio between the amplitude of the reference wave (V_r) and the amplitude of the carrier (V_c).

$$M = \frac{V_r}{V_c} \qquad (6.2)$$

In figure 6.5, M is equal to 0.6. By observing these waves, you can see that the value of M determines the pulse width of each pole voltage; therefore it controls the inverter output voltage. Generally, the amplitude of the carrier wave is fixed and is the reference wave which controls the modulation index and output voltage. When M is zero, the voltages V_{A0}, V_{B0} and V_{C0} of figure 6.5 are symmetrical unmodulated square wave and the instantaneous voltage V_{AB}, is always zero [7].

For small values of M, the output voltage pulses are very thin, but increasing M, the pulse width increases proportionally, in turn increasing volt-second area for half cycle and the fundamental voltage amplitude. When M is close to 1, the output is as would be without the PWM technique [7].

V/f CONSTANT RATIO

Varying simultaneously the carrier wave frequency and reference wave frequency with their phase shift is possible to adjust the frequency of the inverter. These conditions are achieved when the two waves are generated by the same common oscillator. In the figure 6.5 you can see that the duration of each pulse in the voltage output is proportional to the modulation index (M) and also is proportional to the reference wave period, T. Then, the pulse duration, T_p, is proportional to M and T, or M/f, where f is the frequency of the reference wave. If the amplitude of the reference wave is varied linearly with frequency, then the M/f is constant and the duration of the pulse, T_p, is independent of frequency. Consequently, the volt-seconds area per half cycle is the same at all frequencies, which means an operation with volts/hertz constant ratio. Or from another point of view, because the fundamental voltage amplitude is a linear function of M, a constant ratio of M/f implies V/f constant [7].

6.1.3. Sinusoidal PWM

In the square PWM technique explained above, the reference wave is a square phase. The frequency, amplitude and harmonic content of the signal reference are reproduced at the output of the inverter and therefore, the lower-order harmonics of the reference wave appear on the output waveform. However, most AC motors are designed to operate with a sinusoidal source, so the output of the inverter should be as sinusoidal as possible. For this purpose, the reference wave must be replaced by a sine wave to achieve a PWM output where the pulse width is modulated sinusoidally in each half cycle. This technique is known sinusoidal PWM, or subharmonic PWM [7].

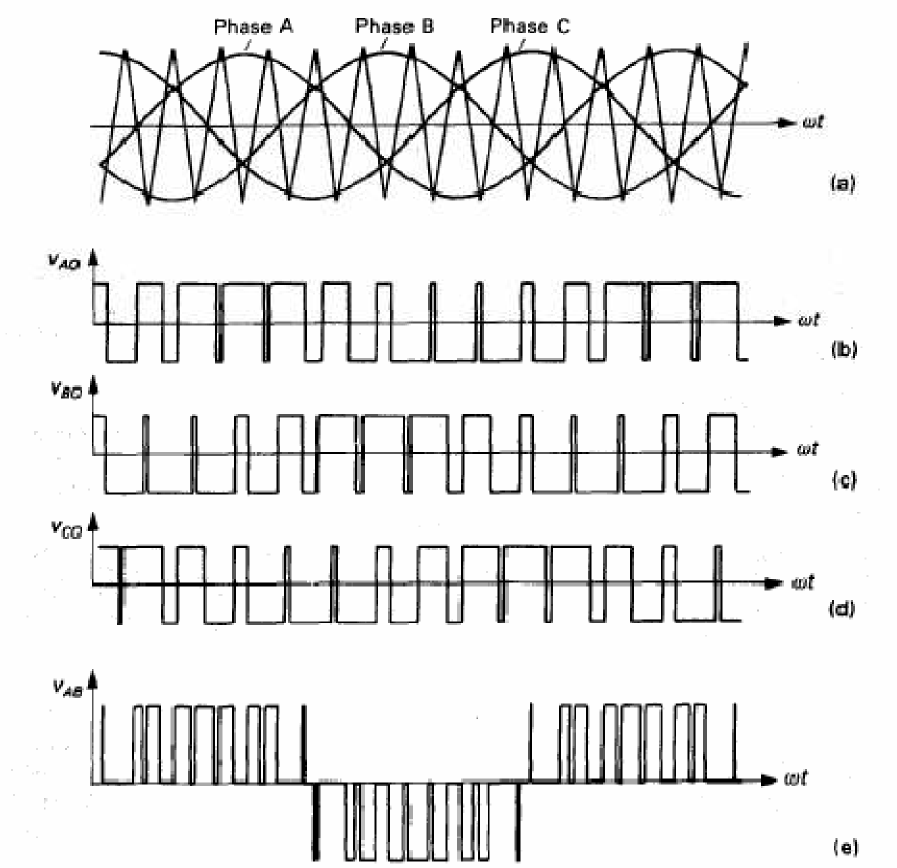

Figure 6.6 Output voltages from three-phase inverter controlled by sinusoidal PWM. (a) Comparator input voltages; (b), (c), (d) pole voltages; (e) line voltage.

As I said before, each phase of the inverter is fed by a comparator for the two waves, the reference sine wave and triangular carrier wave, which is common to all phases.

Again, p must be a multiple of three to ensure the 120 degrees phase shift in output voltages. The triangular carrier has fixed amplitude. The output voltage control is carried out by varying the amplitude of the sine wave. This variation alters pulse widths in the output voltage, but preserves the pattern of sinusoidal modulation.

In figure 6.6, p is equal to nine and the modulation index is nearly 1. The voltages corresponding polar V_{A0}, V_{B0}, V_{C0} and the resultant line-line voltage, V_{AB}, is shown in figure 6.6 b, c, d and e.

The operation by an adjustable frequency modulated sine wave in the output of the inverter for speed control of an AC motor requires the generation of the three sine waves with variable amplitude and frequency. If the motor operates at very low speeds, the reference oscillator must be capable of low frequency to zero hertz. With traditional analog circuits, is very difficult to generate a sinusoidal reference wave without having problems of DC offset and deviation parameters. Consequently, many inverters adopt the PWM square; however, the sinusoidal PWM implementation has been facilitated by modern digital techniques using programmed memory or integrated circuits [7].

6.1.4. Digital control of a PWM inverter

In recent years, the use of digital techniques for PWM waveform generation has increased a lot. Sinusoidal PWM technique uses a modulated sine wave, which is compared with a triangular carrier to determine the inverter switching moments. This technique is known as natural sampling PWM and has been widely adopted for its ease of analog implementation. By means of digital techniques, the reference sine wave can be stored as a table in memory ROM and the values of the sine wave is accessed at a speed corresponding to required fundamental frequency. A triangular carrier wave is generated using a counter and the two waves are compared digitally. However, the natural sampling is essentially an analog technology and this form of digital implementation is not very effective: in a PWM inverter controlled by a microprocessor, it is difficult to estimate the pulse width of the signal by natural sample because they are not defined by any analytical expression [7].

6.1.5. Regular Sampling PWM

An alternative digital type is shown in figure 6.7. The modulating sine wave is now sampled at regular intervals corresponding to positive peaks of the carrier. The sample-and-hold circuit maintains a constant level until it performs the following sample. This process results in a staggered version, or modulated in amplitude, of the reference wave. This staggered waveform is compared with triangular carrier and the points of intersection determine the inverter switching moments [7].

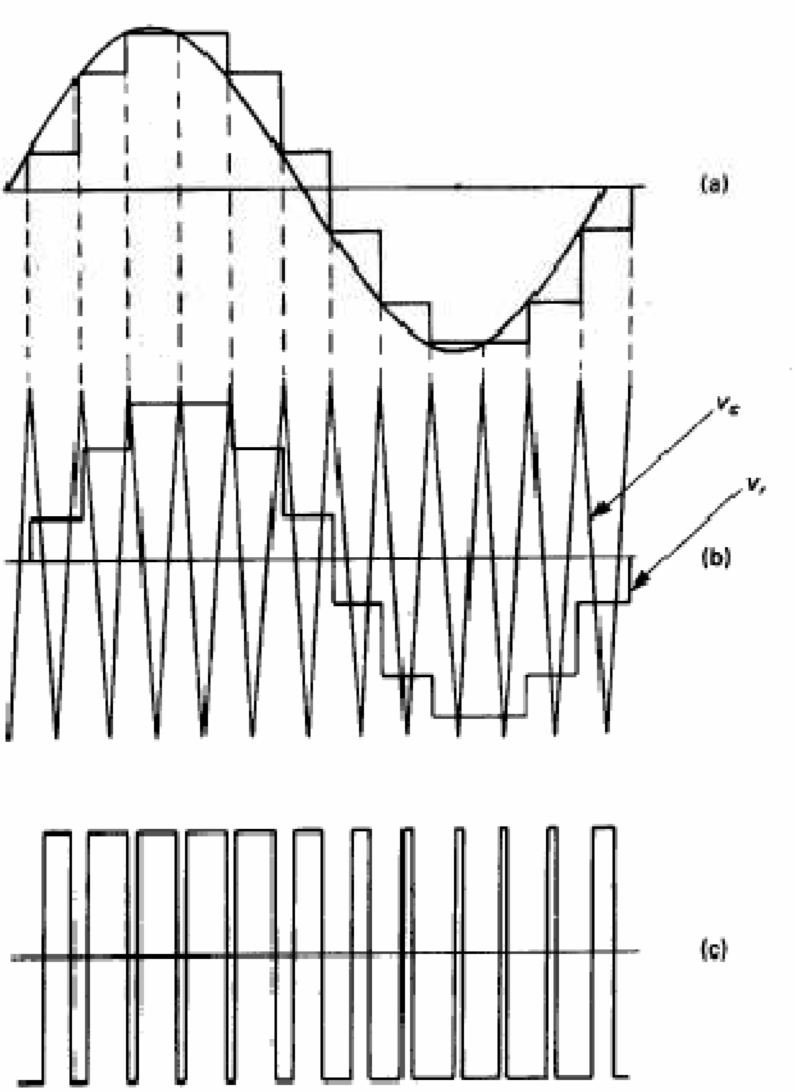

Figure 6.7 Regular Sampling PWM. (a) Modulating signal and sample-and-hold version. (b) Comparator input voltages. (c) Comparator output voltage or pole voltage.

The sample-and-hold version of the modulating wave has a constant magnitude for each pulse. Therefore, the pulse width is proportional to the height of the step and the half of each pulse occurs at evenly spaced intervals. Hence it is called regular or uniform sampling.

In a system implemented by a ROM, there is a substantial reduction of required memory, compared to the natural sampling technique. Figure 6.7 shows that the number of sine values required to define a complete cycle of sample-hold version of the modulating wave is equal to the ratio of carrier used; while in natural sampling, is required a sine wave and the definition of a complete cycle at intervals of 0.5 degrees, which requires 720 values [7].

6.2. Development of the PWM for controlling the inverter

6.2.1. First design: analog circuit

In the beginning it was decided to generate the PWM waves by using analog circuits, using 555 chips and displacement registers, as figure 6.8 shown.

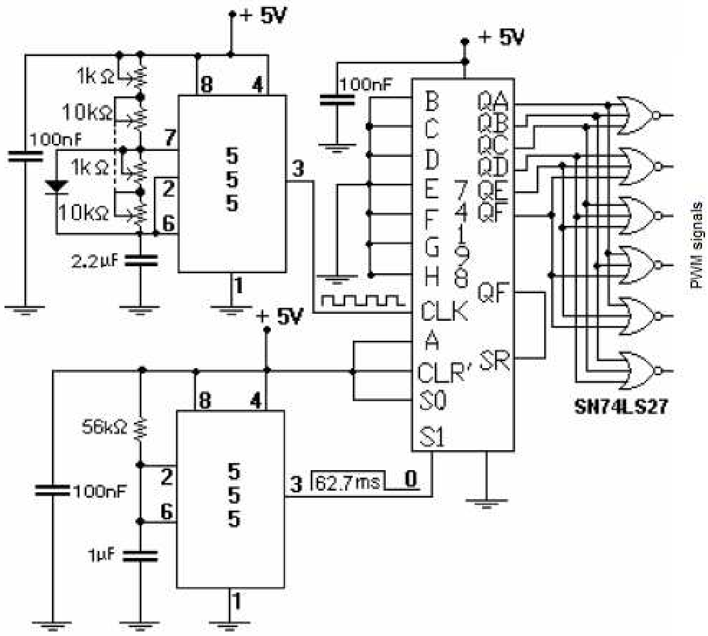

Figure 6.8 Six PWM analogic generator

The advantages of this circuit are the simplicity, low cost and the facility to find these components. On the other hand, this analog technique has less flexibility than using a microcontroller because; the entire components are analog and are hard to change. In addition, microcontroller is a dynamic device, which can control a lot of things besides the speed of the motor, for example: perform lower priority tasks, such as diagnostics, self-test, fault monitoring and soft start-up and shutdown sequencing (see Annex A about soft-starters). Nowadays, microcontrollers are not expensive, which means that using a microcontroller is not an economical issue. Moreover, microcontroller is a unique chip, thus space used to implement the PWM generator circuit is smaller than analog techniques [17].

6.2.2. Second design: microcontroller

Because of the failed attempt to generate PWM waves by using the analog circuit (because this circuit is only to generate PWM waves with 120 degrees phase shift); and also the advantages of the microcontroller, as mentioned above. It was decided to implement PWM techniques by means of a microcontroller to control the three-phase inverter bridge, figure 6.9.

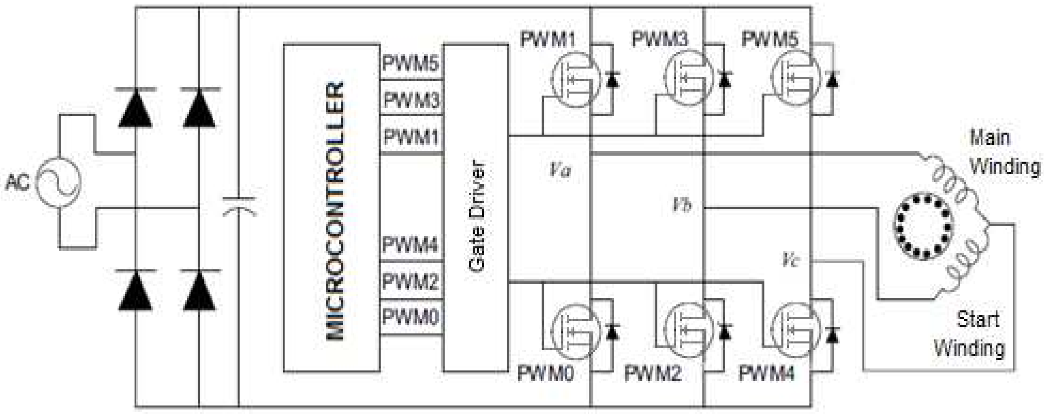

Figure 6.9 Three-phase inverter bridge controlling by microcontroller

Afterward, the first thing was the selection of the microcontroller. There are lots of different microcontrollers in the stores by different companies. I only studied PIC microcontrollers by Microchip. For this reason, I decided to work with this kind of microcontrollers.

There is a lot of information about PWM generation using the regular sampling techniques (section 6.1.5) in the web site of Microchip. About this method, there are two ways to generate PWM, hardware PWM and software PWM and they are both complex. But the software PWM is a little bit easier than hardware PWM. The selected microcontroller to generate software PWM waves is the PIC16F72 because it is one of the simplest and low cost general purpose microcontrollers of Microchip [19, 20, 21, 22].

Figure 6.10 PIC16F72

6.2.2.1. PIC16F72

The PIC16F72 belongs to the middle range family of the PIC microcontrollers. The program memory contains 2000 words, which translate 2048 instructions, since each

14-bit program memory word is the same width as each device instruction. The data memory (RAM) contains 128 bytes.

There are 22 input/output pins that are user configurable on a pin-to-pin basis. Some pins are multiplexed with other device functions. These functions include:

- External interrupt
- Change on PORTB interrupt
- Timer0 clock input
- Timer1 clock/oscillator
- Capture/Compare/PWM
- A/D converter
- SPI/I^{2}C

In the figure 6.11 is shown the block diagram of the PIC16F72, in which the principal parts and functions are represented with the relation between each of them [18].

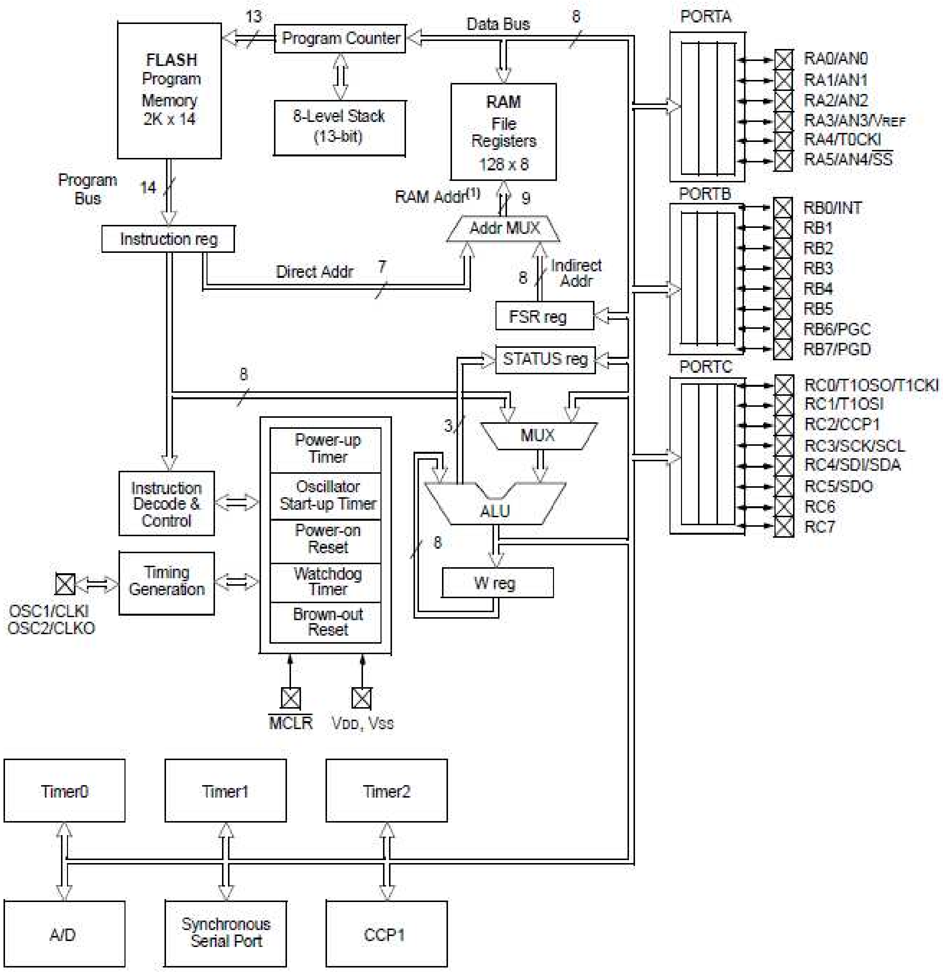

Figure 6.11 PIC16F72 block diagram

6.2.2.2. Sinusoidal PWM Implementation using PIC16F72

To control a three-phase inverter bridge is necessary to create a three PWM pairs with complementary outputs. Obviously in each complementary pair of PWMs is required a dead time between any off and on switching moments to avoid a short circuit in the DC bus. As it was said, PIC16F72 only have one PWM generator by hardware, but to control a three-phase inverter bridge is necessary six PWM. Therefore, this has to be implemented by software, using a general purpose timer and six output pins.

The maximum operating frequency for this PIC is 20 MHz; which is the frequency used in this thesis. The PWM frequency is approximately 8 KHz, which is managed using the Timer1 of the PIC.

To make clear, in each period of the PIC clock, four instructions are carried out. As the frequency of the PIC is 20 MHz, the instruction cycle is 5 MHz or in other words: one instruction is done each 200 ns. Timer1 is counted up from 00 to 634, thus 200 ns multiplied by 634 is approximately 8 KHz, our PWM frequency for the first implementation.

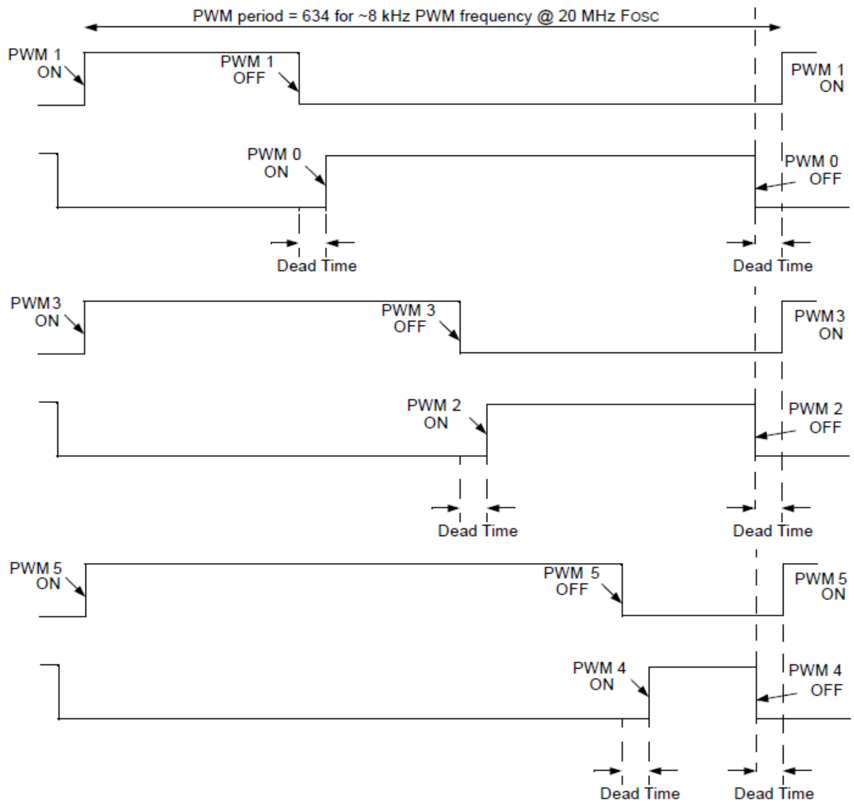

Figure 6.12 Six PWM output waves

At the beginning of the cycle (Timer1=00), the PWMs controlling the upper switches are turned on. Based on the individual PWM duty cycle, the corresponding PWM output is turned off. After five instruction cycles, the complementary PWM is turned on. This gives a dead time of 1.2 µs (200 ns*6=1.2 µs). When the count reaches 624, all outputs are turned off. A new PWM cycle starts after 8 instruction cycles. When Timer1 value overflows, Timer1 interruption happened, therefore the corresponding odd PWM is turned off and the corresponding even PWM is turned on after dead time. This is done for all three pairs of PWM as is shown in figure 6.12.

Sinusoidal PWM technique is used to change the duty cycles, which is performed by using a table of values that change sinusoidally. This table is loaded into the microcontroller memory (RAM) and is accessed cyclically; multiplying this table value by output frequency gets the value of duty cycle corresponding to each value in the table, resulting in a sinusoidal variation of output duty cycle. Since the inverter is three phase, three pointers are used: for V_a a 180 degrees phase shift with respect to V_b and Vc a ±90 degrees shift with respect to V_a and V_b.

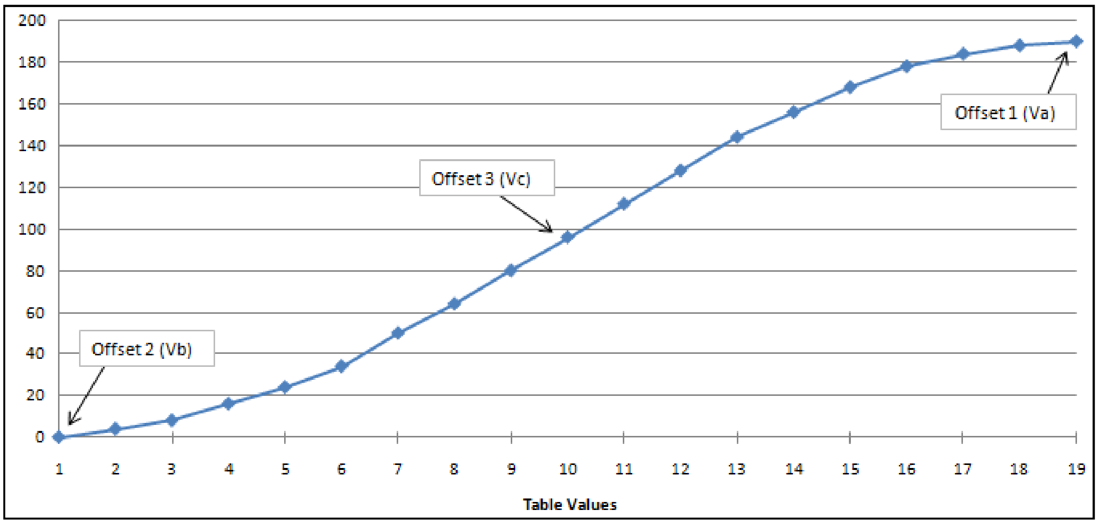

Figure 6.13 Sine table values and offset pointers

Sine table values and pointers are shown in the figure 6.13. The range of this values are from 0 to 255, because the variable used is 8 bits; for the realization of this project is used 19 values in the sine table, so the resolution is 10 degrees for each value from the sine table and a total of 36 points to synthesize a complete cycle of the output signal.

The output frequency is provided by Timer0 of the microcontroller, which interrupts (Timer0 overflow) at the end of duty cycle and change to the following value, to get the new PMW duty cycle advanced by 10 electrical degrees on the sine table (one table value). Output voltage generation process controlling by Timer0 interruptions is shown in figure 6.14. Each interruption of Timer0 corresponds to a sine table value and each interruption of Timer1 corresponds to transistors switching moments.

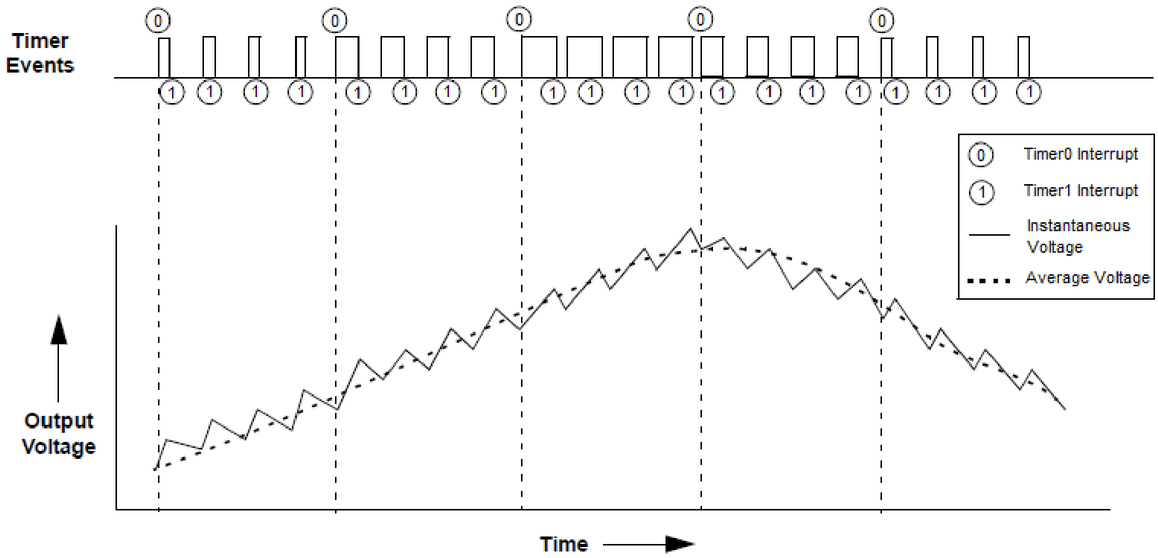

Figure 6.14 Instantaneous and average voltage generated by Timer0 interruptions and Sine table values.

Figure 6.14 shows that for each duty cycle value is generated an instantaneous voltage and the sum of the voltage through time gives the average output voltage, which is of sinusoidal type. The half cycle output voltage shown in figure 6.14 corresponds to the voltage on a transistor of half bridge of the inverter. The output frequency is given by the microcontroller Timer0 as follows [19, 20, 21, 22]:

$$\boldsymbol{Timer0\ reload\ value = 0xFF - \frac{\frac{F_{OSC}}{4}}{2(STV-1)\times Timer0\ Pr \times New\ Freq}} \qquad (6.3)$$

Where:
F_{OSC} = The operating frequecy of the PIC (20MHz)
STV = Sine table values (19)
Timer0 Pr = The Timer0 prescaler (128)
New Freq = The digital value of the potentiometer connected to the ADC converter

6.2.2.3. Overview of PIC code

Code used to generate the PWM waves with PIC microcontroller is shown in the annex B. However, it is necessary an explication to understand the program.

INITIALIZATION

First of all, it is configured the different PORTs of the microcontroller. The PORTB is an input/output port, which shows the state of the program, controlling the LEDS for stop, run and direction and is also the input for the push button for stop/run and for the push button for direction change. The PORTC is initializated to output PWMs.

Analog-to-digital converter (ADC) is initialized to read the frequency reference, which is read using a potentiometer to A/D channel 0 (AN0).

Timer 0 and 1 are initialized. Timer 0 is used for setting the motor frequency based on the potentiometer setting. Timer1 is initializated with 16-bit operation and 1:4 prescale. In addition ,Timer0 overflow and Timer1 overflow are enabled.

The sine table and its offsets are loaded into RAM, because the access to the RAM table is faster.

MAIN ROUTINE

PIC is always looping in this routine and also it is checking if one of the two push buttons is pulsed.

In the beginning of the loop, it is checked if Timer0 interrupts (using a flag). If the answer is no, it will continue only controlling the inputs (push button and potentiometer). If the answer is yes, then it will do the next tasks:

- New PWM duty cycle is calculated by the subroutine UPDATE_PWM_DUTYCYCLES. This subroutine will update the PWM duty cycle according to the table and scales the PWM value from the table based on the output frequency to keep constant the V/f ratio and loads them in appropriate register.
- PWM duty cycle sorting is handle by the subroutine PRIORITIZE_PWMS. PWM duty cycles calculated earlier are sorted in ascending order, so that the duty cycle with minimum ON time can be addressed first and PWM with maximum duty cycle last. Corresponding flags are set to indicate which PWM duty cycle corresponds to which PWM output.
- Offset pointers used to generate the sine wave should advance by 10 degrees in the sine table. This is done by the routine UPDATE_TABLE_OFFSET.

- Timer0 reload value is calculated by the subroutine CALCULATE_NEW_SPEED. Timer0 is used for setting the motor frequency. As it was mentioned in the equation 6.3, Timer0 reload value is calculated based on three factors: first is the frequency reference input from the potentiometer, second is the number of sine table values and third is the microcontroller operating frequency.
- ADC result is handled by the subroutine AD_CONV_COMPLETE and this result is the new frequency for the motor, which has lower (15Hz) and upper (58Hz) limits.

INTERRUPT SERVICE ROUTINE (ISR)

Interrupt service routine is enable when Timer0 overflows or Timer1 overflows. After the interruption, program will be back on the same instruction as it was before the interruption.

- Timer0 ISR: A flag is set to indicate that the whole mains routine has to be made and the Timer0 register is reloaded with the value corresponding to the motor frequency reference.
- Timer1 ISR: In the first of three Timer1 overflow, the corresponding odd PWM output is turned off in each ISR and complementary output is turned on after a dead time (1.2 µs). In the fourth Timer1 overflow, the PWM cycle is restarted. All PWMs are turned off and the timer is loaded with the value corresponding to the lowest duty cycle value. This is repeated for each PWM cycle.

6.2.2.4. Schematic for the PIC

In the figure 6.15 is shown the circuit for the PIC along with all the elements that make it works. There are also the inputs of the push buttons and the potentiometer. PIC status and in turn the motor status is known due to LEDs. Finally, the PWM outputs go to the optocouplers.

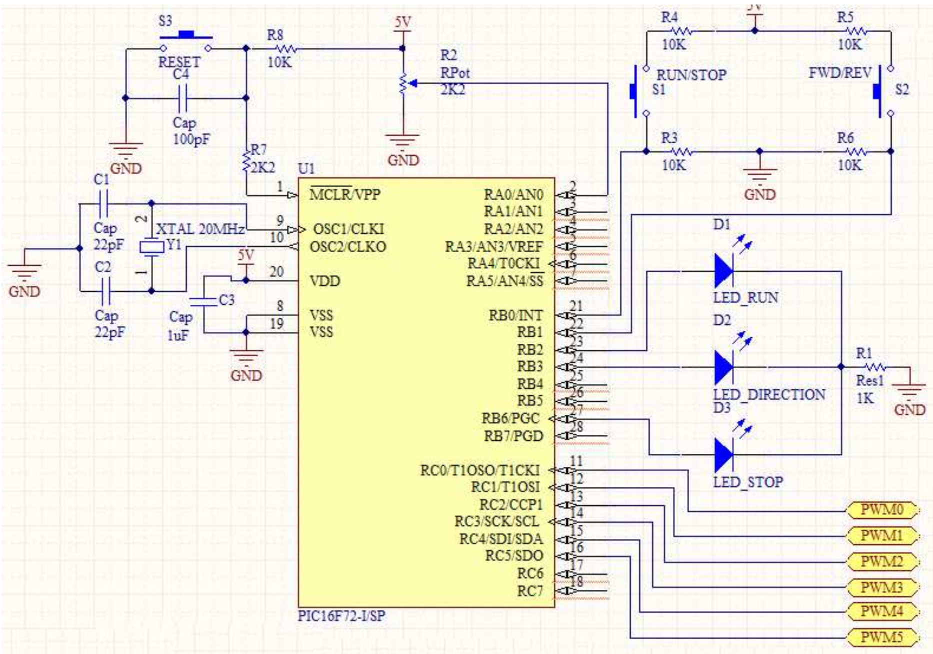

Figure 6.15 Schematic for PIC16F72

6.2.2.5. PWM waves results

Output PWM waves are shown in the following pictures. In this pictures, it is possible to see the different features of this waves and the relation between the PWM waves from each of the three legs of the bridge. In the figure 6.16, you can see the PWM wave for the upper MOSFET and his complementary, which is the PWM wave for lower MOSFET of the bridge. Note: the followings pictures are from the ouput of the optocouplers.

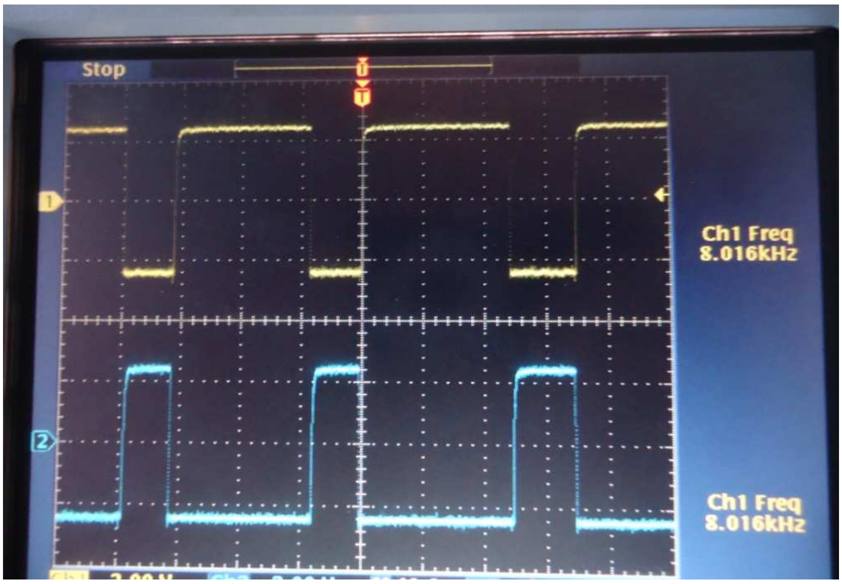

Figure 6.16 PWM waves for the upper and lower MOSFET of one leg of the bridge.

6.2.2.5.1. Dead time between complementary PWM waves

As I said before, there is a dead time among complementary PWM waves. In the figure 6.17 is shown the dead time when lower MOSFET is turned off and upper MOSFET is turned on. And, in the figure 6.18 is shown the dead time when upper MOSFET is turned off and lower MOSFET is turned on. You can see in the figure the duration of both dead times.

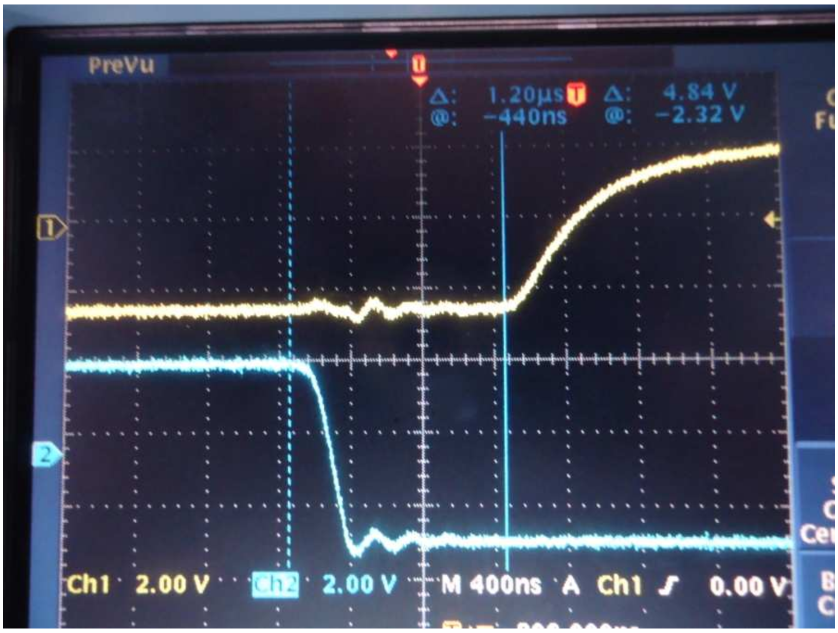

Figure 6.17 First deadtime

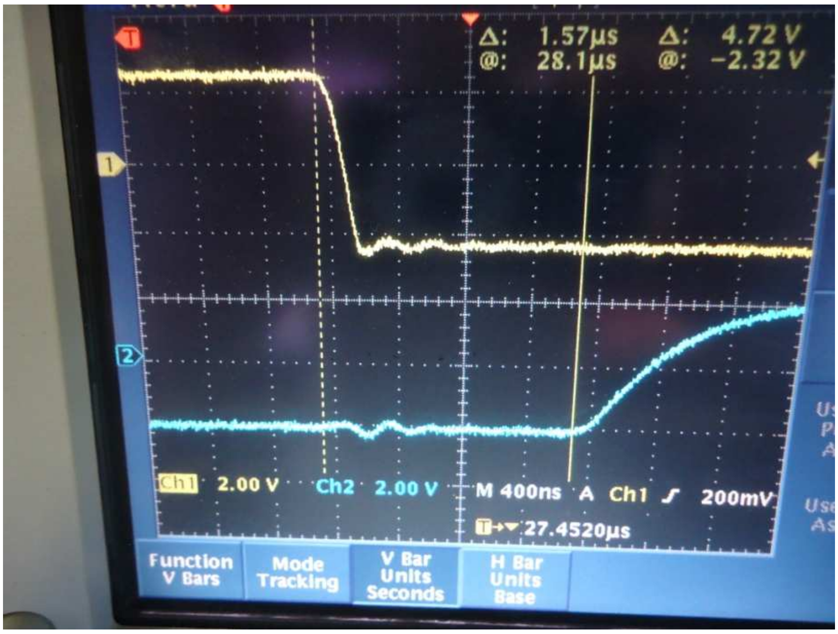

Figure 6.18 Second deadtime

6.2.2.5.2. Output waves

Output waves are the waves that fed motor windings. Thus they are the difference between waves from each leg of the bridge. In the figures 6.19 and 6.20, it is shown the wave for main winding with different frequencies.

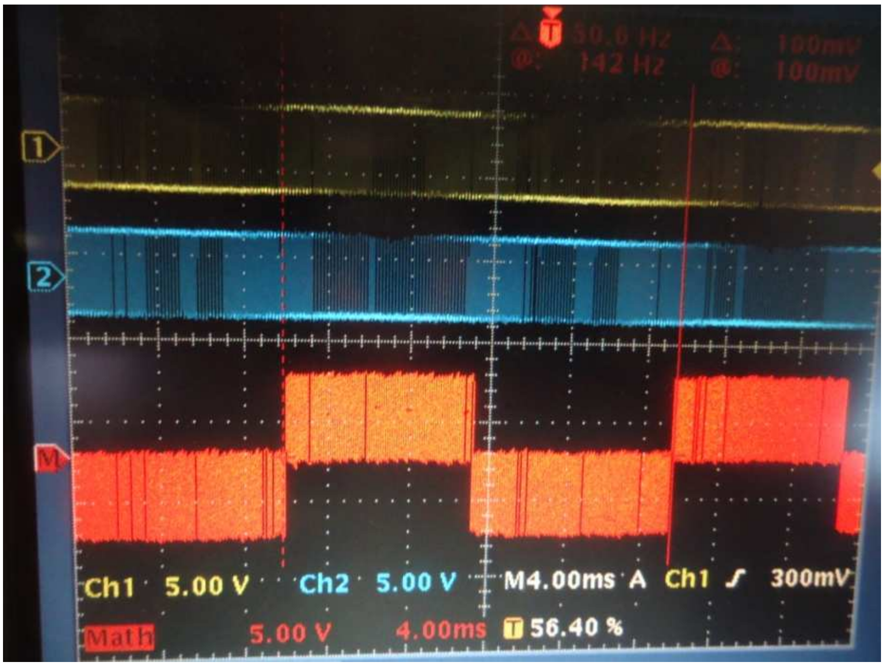

Figure 6.19 Main winding voltage at 50Hz

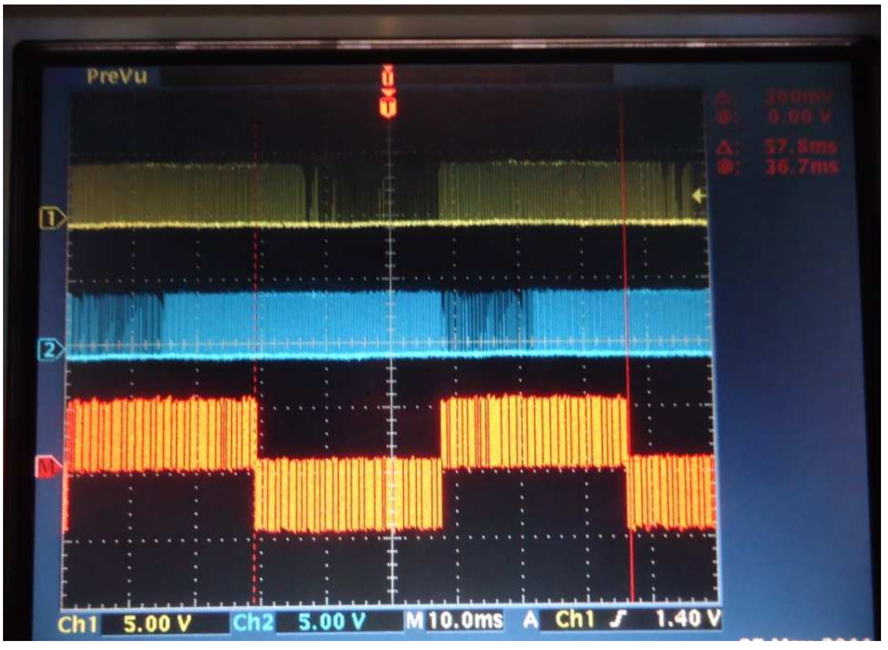

Figure 6.20 Main winding voltage at 17Hz

6.2.2.5.3. Difference among waves from each leg of the bridge

The figures 6.21 and 6.22 show the phase voltages V_a, V_b and V_c, where V_a is the first one, V_b is the second one and V_c is the third one. The phase difference between V_a and V_b is 180 degrees in both figures. However, in the figure 6.21, the phase difference between V_a and V_c is 90 degrees, thus motor will rotate in forward direction.

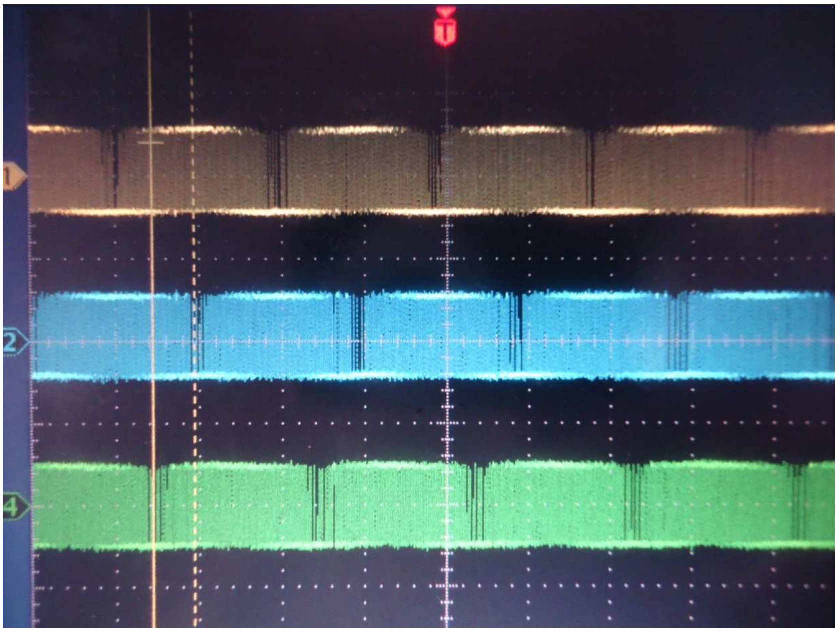

Figure 6.21 Phase voltages V_a, V_b and V_c.

However, in the figure 6.22, phase difference between V_a and V_c is 270 degrees, thus motor will rotate in reverse direction.

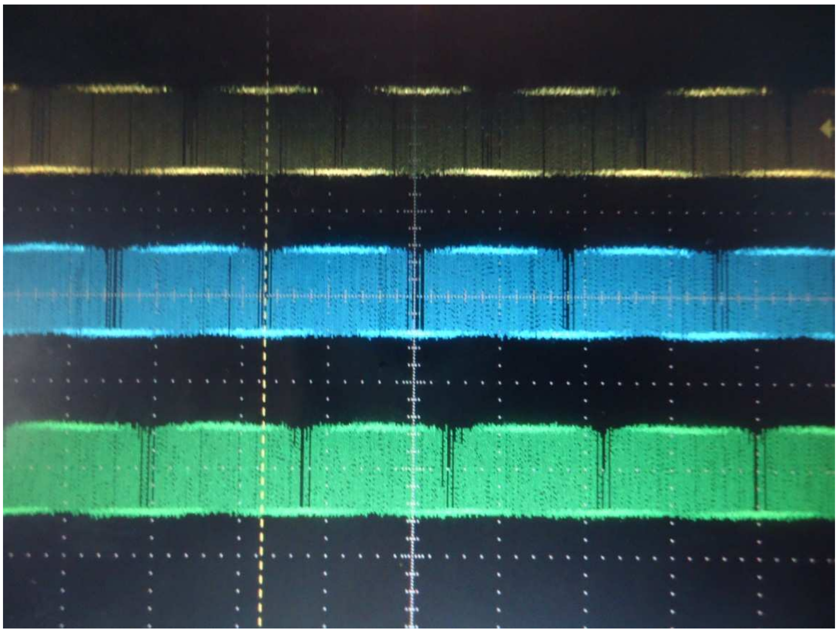

Figure 6.22 Phase voltages V_a, V_b and V_c.

6.3. Optocouplers

6.3.1. Selection of the optocoupler

An optocoupler was selected with two input and two output signals to use three optocouplers which generate the six signals required by the gate driver to drive the MOSFETs of the inverter. The optocoupler used in this application is the HCPL-2530 consisting of a pair of LEDs emitting transistors targeted at high-speed photodetectors (1Mbit/s), figure 6.23. The polarization of the transistor is due to the light emitted by the LED having and optical isolation.

Figure 6.23 Optocoupler HCPL-2530

6.3.2. Features of the selected optocoupler

This device has a separate connection for the polarization of the photodiode that improves the speed greatly over conventional optocouplers by reducing the base-collector capacitance of the input transistor. It maintains isolation between the control system and power system with a 2500V of isolation voltage. Physically, it is an eight-pin integrated circuit as shown in figure 6.24.

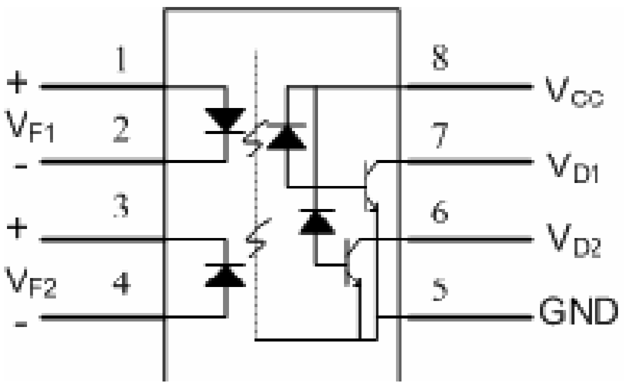

Figure 6.24 Internal circuit of HCPL-2530

6.3.3. Schematics for Optocouplers

The optocouplers are a protection for the control stage, the microcontroller. They isolate the outputs of the PIC of the power circuit. This isolation is necessary because the PIC does not work with the high voltage and high current as the motor. The schematic for isolation is shown in Figure 6.25.

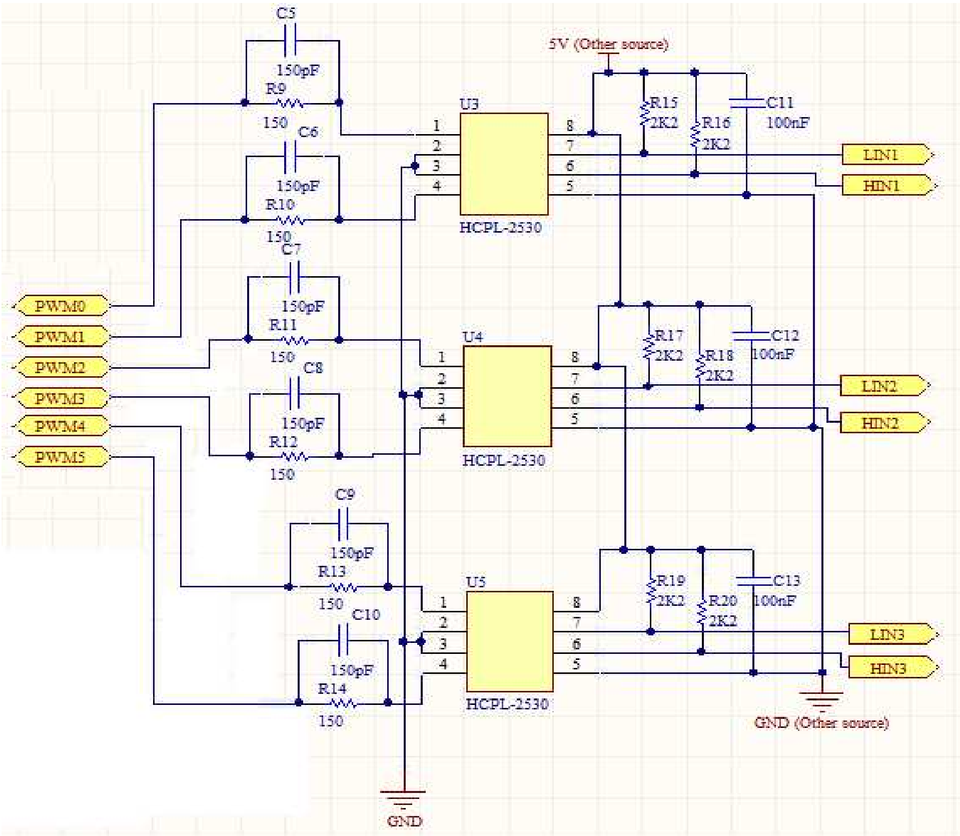

Figure 6.25 Schematic for optocouplers

There are three optocouplers, each optocoupler get two 5V PWM signals and the reference coming from the PIC. These devices are supplied with a 5V supply. The PWM output has a 5V referenced to sources of 5V and 15V feeding the MOSFET driver IR21365 or inverter module FCBS0650, which are shown below. The frequency PWMs to the optocouplers is 8 kHz. Therefore, the PWM outputs of the optocoupler have the same frequency. Output signal of the optocouplers is reversed compared to input.

The input resistances to the optocoupler limit the feeding current to internal diodes. These resistances are calculated based on the signal voltage applied to the diodes, the maximum current that can give the PIC and the current required by the optocoupler. PWM signals applied to the input of the optocouplers are 5V. The PIC provides a current of 25 mA and the optocoupler works with a maximum current of 50 mA [23]. Figure 6.26 shows the circuit of each input of the optocoupler.

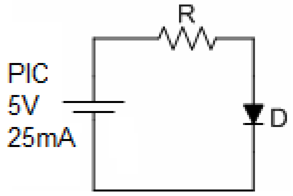

Figure 6.26 Optocouplers input circuit

To calculate the resistance R, which will limit the supply current of optocouplers; it must be consider the optocoupler diode voltage drop. This diode has a drop of 1.45V [23]. Therefore, the resistance R is:

$$\boldsymbol{R = \frac{V}{I} = \frac{5 - 1.45}{25 * 10^{-3}} = 142\ \Omega} \qquad (6.4)$$

It was decided to use 150Ω resistance because this is the closest commercial value that can be used. The capacitors in parallel with the input resistance of the optocoupler, as shown in figure 6.25, accelerate the status change time of input signals and also reduce oscillations that might be presented from these changes. It was implemented a 150 pF capacitor. In addition, in the figure 6.25 are shown 2.2kΩ resistances, which are load resistors used to decrease the turn-on time of the optocoupler transistor, hence improves the speed of changes in output state. Finally, 0.1µF capacitor performs as a decoupling capacitor. These items are recommended by [23, 24].

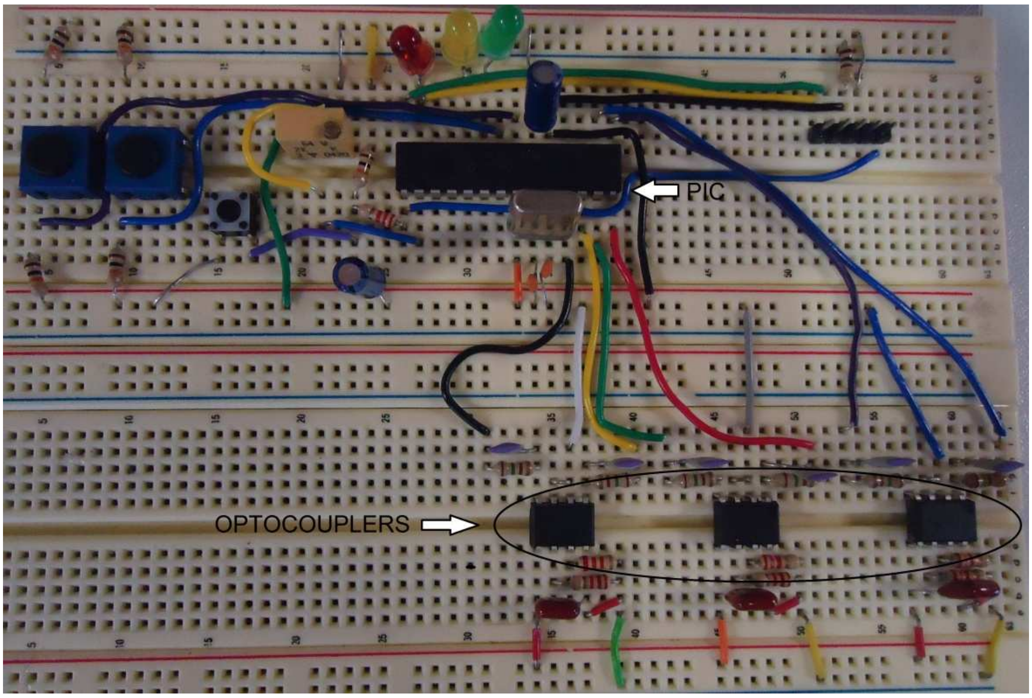

Figure 6.27 Implementation of the control logic circuit with PIC and optocouplers

6.4. Selection of the three-phase inverter components

6.4.1. First Selection: Driver and MOSFETs

The first selection for the inverter was based on MOSFETs and a MOSFET driver. Because the MOSFETs are inexpensive, have low switching losses, are good for low power applications and have good performance at high frequency.

To turn power MOSFET on, the gate terminal must be set to a voltage at least 5V greater than the source terminal. High side MOSFET of the bridge is not connected to ground, which means that to turn on this MOSFET is necessary to provide to the gate 5V plus the source voltage. And this is achieved using a MOSFET driver with a bootstrap circuit. In addition, the driver gives more current to turn on the MOSFET faster, which means the heat produced is lower. MOSFET drivers have also certain protection schemes and blocking signals to help the operation of the motor.

The MOSFET that I selected is this: FQPF3N80C of Fairchild Semiconductor. And the driver is: IR21365 of International Rectifier.

6.4.1.1. MOSFET FQPF3N80C

The transistors used are the model FQPF3N80C (figure 6.28) of Fairchild Semiconductor, which have internally freewheeling diodes in antiparallel and are capable of support an operational voltage of 800V and 3A at 25°C [16].

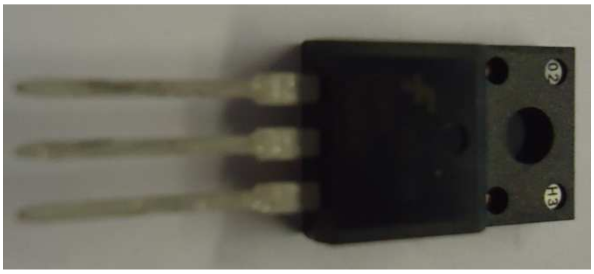

Figure 6.28 MOSFET FQPF3N80C

The features of MOSFET FQPF3N80C are:

- 3.0A, 800V, $R_{DS(on)}$ =4.8Ω when V_{GS} =10 V
- Low gate charge (typical 13 nC).
- Low reverse transfer capacitance (typical 5.5 pF).
- Fast switching.
- Improved dv/dt capability.

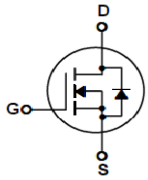

Figure 6.29 FQPF3N80C diagram

6.4.1.2. MOSFET Driver IR21365

The driver used is the model IR21365 of International Rectifier, which is high voltage, high speed power MOSFET driver with three independent high and low side referenced output channels for three-phase applications. A current trip function which terminates all six outputs can be derived from an external current sense resistor. An enable function is available to terminate all six outputs simultaneously. An open-drain fault signal is provided to indicate that an overcurrent or undervoltage shutdown has occurred.

Figure 6.30 MOSFET driver IR21365

Overcurrent fault conditions are cleared automatically after a delay programmed externally via an RC network connected to the RCIN input. The floating channel can be used to drive N-channel power MOSFETs in the high side configuration which operates up to 600V [25].

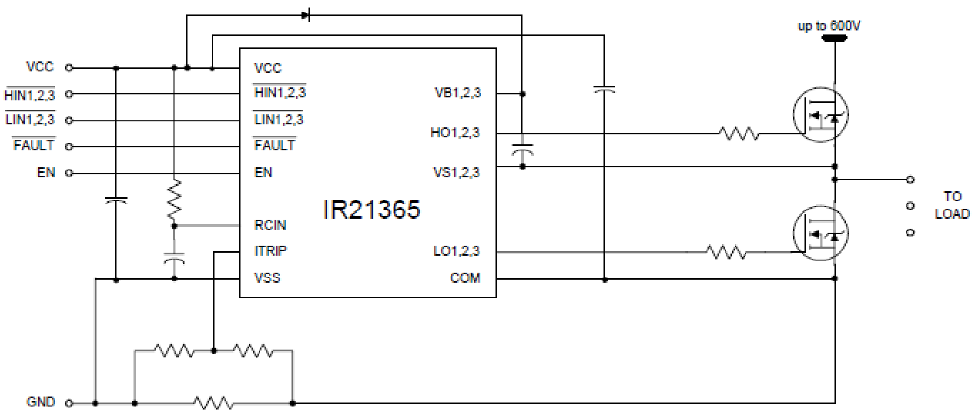

Figure 6.31 IR21365 Typical connection

The features of MOSFET driver IR21365 are [25]:

- Floating channel designed for bootstrap operation.
  - Fully operational to +600V.
  - Tolerant to negative transient voltage - dV/dt immune.
- Gate drive supply range from 12 to 20V.
- Undervoltage lockout for all channels.
- Over-current shutdown turns off all six drivers.
- Independent 3 half-bridge drivers.
- Cross-conduction prevention logic.
- Low-side outputs out of phase with inputs. High side outputs out of phase with inputs.
- 3.3V logic compatible.
- Lower di/dt gate driver for better noise immunity.
- Externally programmable delay for automatic fault clear.

6.4.1.2.1. Bootstrap circuit

This V_{bs} supply voltage is a floating supply that sits on top of the V_s voltage. There are a several ways in which the V_{bs} floating supply can be generated, one of these is using the bootstrap method described here. This method is simple and inexpensive but has some limitations: duty cycle and on-time are limited by the requirement to refresh the charge in the bootstrap capacitor (C_{bs}). The bootstrap supply is formed by a diode and capacitor combination as shown in figure 6.32.

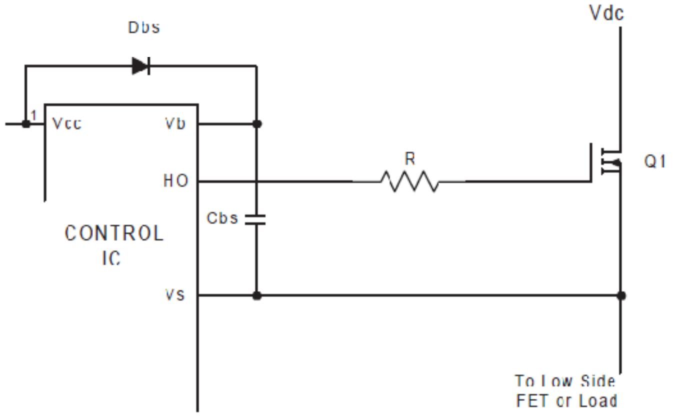

Figure 6.32 Bootstrap circuit

The bootstrap circuit operation is as follows: when V_s is pulled down to ground through lower MOSFET, bootstrap capacitor is charged through the bootstrap diode (D_{bs}) of the 15V V_{cc} supply. Therefore, it provides a supply to V_{bs}. When V_s is taken to a higher voltage by high-side MOSFET, the source V_{bs} float, the bootstrap diode is forward biased reverse and it blocked the voltage. This source needs to be in the range of 10 to 20 V to ensure that the integrated circuit can be switched to control MOSFETs being driven.

There are five influencing factors which contribute to the supply requirement from the V_{bs} capacitor:

1. Gate Charge required enhancing MOSFETs.
2. I_{qbs} - quiescent current for the high side driver circuitry.
3. Currents within the level shifter of the control IC.
4. MOSFETs gate-source forward leakage current.
5. Bootstrap capacitor leakage current.

Factor 5 is only relevant if the bootstrap capacitor is an electrolytic capacitor and can be ignored if other types of capacitor are used. Therefore it is always better to use a non-electrolytic capacitor. In this design I used Tantalum capacitors.

CALCULATING THE BOOTSTRAP CAPACITOR VALUE

The minimum bootstrap capacitor value can be calculated from the following equation:

$$\boldsymbol{C \geq \frac{2\left[2Q_g + \frac{I_{qbs(max)}}{f} + Q_{ls} + \frac{I_{Cbs(leak)}}{f}\right]}{V_{cc} - V_f - V_{LS} - V_{Min}}} \qquad (6.5)$$

Where:
Q_g = Gate charge of high-side FET
f = frequency of operation
I_{Cbs} (leak) = bootstrap capacitor leakage current (0 for Tantalum capacitors)
$I_{qbs(max)}$ = Maximum VBS quiescent current
V_{CC} = Logic section voltage source
V_f = Forward voltage drop across the bootstrap diode
V_{LS} = Voltage drop across the low-side FET or load
V_{Min} = Minimum voltage between VB and VS.
Q_{ls} = level shift charge required per cycle (typically 5 nC for 500 V/600 V MOSFETs)

Substituting the above values in equation 6.5 with values of MOSFET and driver datasheets [16, 25]:

$$\boldsymbol{C} \geq \frac{2\left[2 \times 16.5 \times 10^{-9} + \dfrac{120 \times 10^{-6}}{8 \times 10^{3}} + 5 \times 10^{-9} + 0\right]}{15 - 0.55 - 1.4 - 12} = \mathbf{100.9}\ \boldsymbol{nF} \qquad (6.6)$$

Therefore the capacitor must have a value greater than 100.9 nF, but it is recommended that the bootstrap capacitor value is 15 times the value obtained, so that the capacitor used was 1.5 uF.

SELECTING THE BOOTSTRAP DIODE

Calculating the bootstrap diode, it must have a reverse recovery time (t_{rr}) of no more than 100 ns, supporting the supply voltage of the inverter (DC bus voltage) and load circuit current, which depends on MOSFET gate charge and switching frequency. The diode used in this development is the model BYV26D of VISHAY GENERAL SEMICONDUCTOR, which supports up to 800V among terminals, has a 75 ns t_{rr} and supports a current of 1A, thus covering all the requirements for the proper functioning of the driver, for development of this project [26, 27].

6.4.1.3. Overview of the circuit

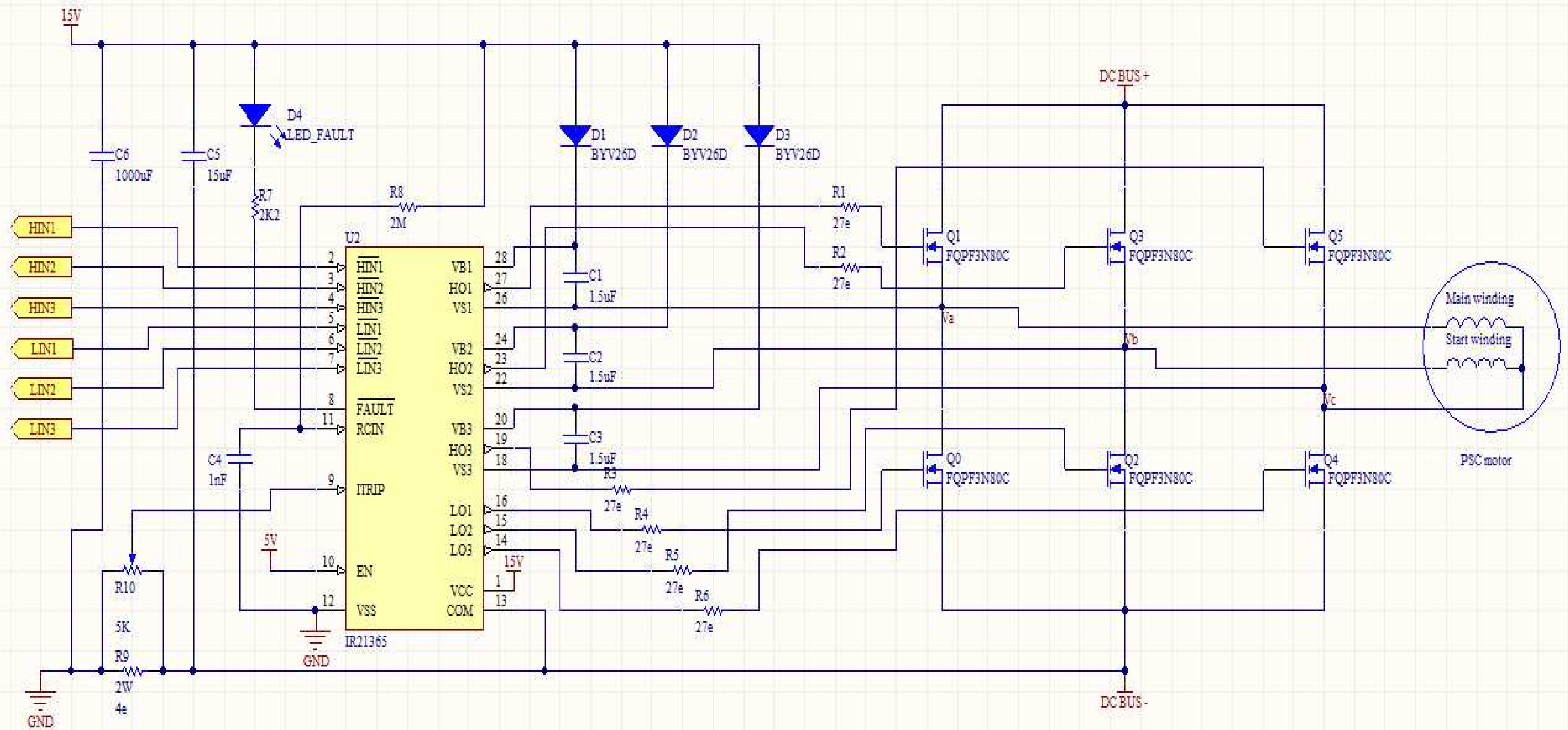

Figure 6.33 Circuit with MOSFETs and driver.

6.4.2. Second selection: Integrated circuit (IC)

After trying to control the motor speed with the first circuit during a while and not getting any result in spite of making endless calculations and reviewing numerous articles on these components.

Mainly due to the problems that came up when the connections between the MOSFETs and driver were made and the sensitivity of these to become unusable very quickly. I decided to use an integrated chip that contains the whole inverter. The selected integrated chip was FCBS0650 of Fairchild Semiconductor (figure 6.34).

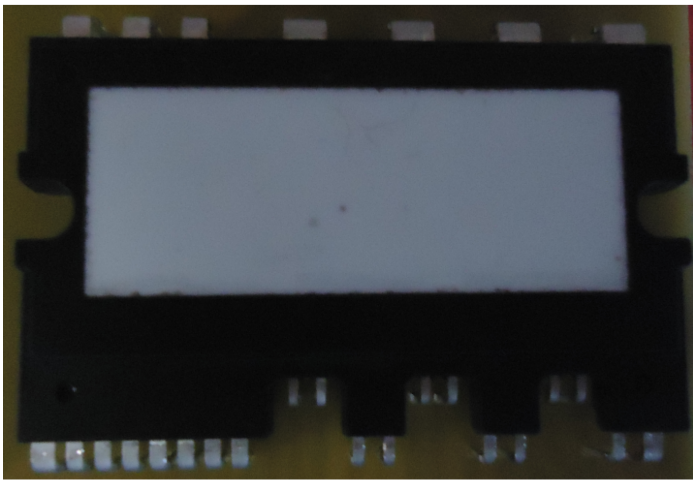

Figure 6.34 FCBS0650

This chip is more expensive, but more suitable for controlling low power AC motors, as our selected motor. Moreover, being an integrated circuit is compact, more reliable, less noisy and more efficient. System reliability is improved by the integrated under voltage lock-out and short circuit protection.

The features of the integrated chip FCBS0650 are:

- 500V-6A 3-phase MOSFET Inverter Bridge including control ICs for gate driving and protection.
- Divided negative dc-link terminals for inverter current sensing applications.
- Single-grounded power supply due to built-in HVIC.
- Very low leakage current due to using ceramic substrate

As it is shown in the figure 6.35, FCBS0650 inverter has internally six MOSFETs and the driver for the MOSFETs. Strictly, it has two differents sides: power side and control side. And this in turn is divided into high-side and low-side. Inverter low-side is composed of three MOSFETs and one control IC driver. This driver has gate driving and protection functions. Inverter high-side is composed of three MOSFETs and three driver ICs for each MOSFET.

Inverter power side is composed of four inverter dc-link input terminals and three inverter output terminals.

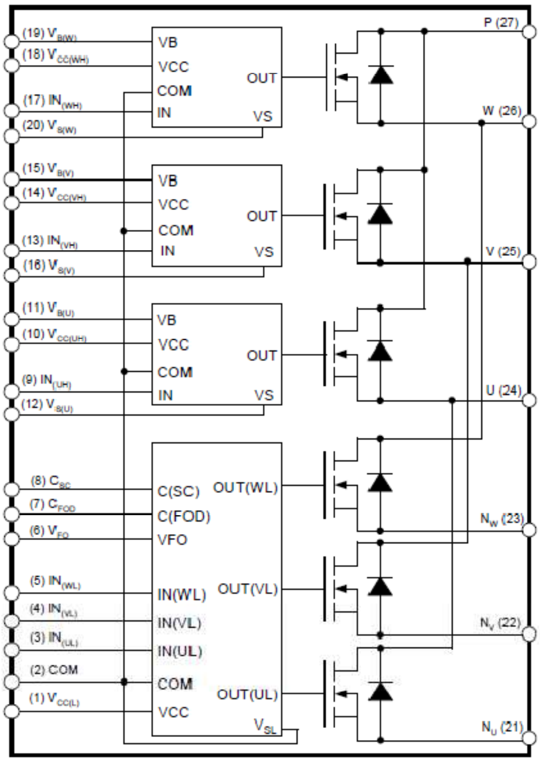

Figure 6.35 Internal circuit of FCBS0650

The inverter module input logic is active-high and there are built-in pull-down resistors, therefore external pull-up resistors are not needed. And V_{FO} output is open collector configured.

Control and gate drive power for the inverter module is normally provided by a single 15VDC supply that is connected to the module V_{CC} and COM terminals. For proper operation this voltage is regulated to 15V and its current supply should be larger than 60mA for inverter module chip only. The control supply is well filtered with a low impedance electrolytic capacitor and a high frequency decoupling capacitor.

High frequency noise on the supply might cause the internal control IC to malfunction and generate erroneous fault signals. To avoid these problems, the maximum ripple on the supply should be less than ±1V/µs. In addition, it may be necessary to connect a 24V, 1W zener diode across the control supply to prevent surge destruction under severe conditions.

The main control power supply is also connected to the bootstrap circuits that are used to establish the floating supplies for the high side gate drives.

When control supply voltage (V_{cc} and V_{bs}) falls down under UVLO (Under Voltage Lock Out= 10V) level, MOSFETs will turn off while ignoring the input signal. To prevent noise from interrupting this function, built-in 15µsec filter is installed in both high-side driver and low-side driver [28].

6.4.2.1. Bootstrap circuit

As I said in the last method with discrete components, there is necessary to provide the supply for the high-side drivers. This supply (V_{bs}) must be in the range of 13-18V to ensure that the high-side drives can fully drive the high-side MOSFETs. The inverter module includes an under-voltage detection function for the V_{bs} to ensure that the high-side drivers do not drive the high-side MOSFETs.

The bootstrap supply is formed by a combination of a diode, resistor and capacitor as shown in figure 6.36. The bootstrap circuit operation was explained in the section 6.4.1.2.1.

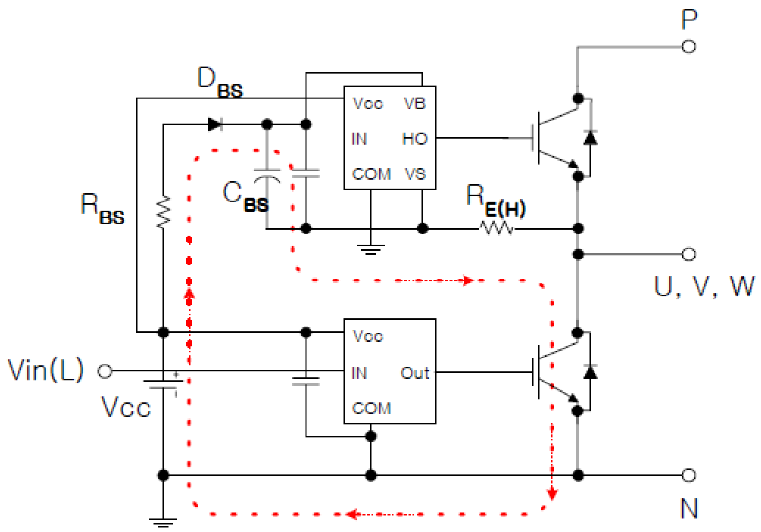

Figure 6.36 Bootstrap circuit

CALCULATING THE BOOTSTRAP CAPACITOR VALUE

The minimum bootstrap capacitor value can be calculated from the following equation:

$$C \geq \frac{I_{leak} \times \Delta t}{\Delta V} \qquad (6.7)$$

Where:
I_{leak} = maximum discharge current of the C_{bs}, recommended 1mA.
Δt = maximum ON pulse width of the high-side MOSFET.
ΔV = the allowable discharge voltage of the C_{bs}.

Substituting the above values in equation 6.7:

$$C \geq \frac{1mA \times 0.125ms}{1V} = 125\ nF \qquad (6.8)$$

Therefore, the capacitor must have a value greater than 125 nF, but it is recommended that the bootstrap capacitor value is 15 times the value obtained, so that the capacitor must be greater 2 uF.

SELECTING THE BOOTSTRAP DIODE

When high-side MOSFET or diode conducts, the bootstrap diode (D_{bs}) supports the entire DC bus voltage. Hence the withstand voltage more than 600V is recommended. It is important that this diode should be fast recovery (recovery time < 100ns) device to minimize the amount of charge that is fed back from the bootstrap capacitor into the V_{cc} supply. Similarly, the high voltage reverse leakage current is important if the capacitor has to store a charge for long periods of time.

The diode used is the same as the circuit with discrete components, BYV26D of VISHAY GENERAL SEMICONDUCTOR, which supports up to 800V among terminals. It has a 75 ns t_{rr} and supports a current of 1A, thus covering all the requirements for the proper functioning of the driver, for development of this project.

SELECTING THE BOOTSTRAP RESISTANCE

A resistor R_{bs} is added in series with the bootstrap diode to slow down the dV_{bs}/dt and it also determines the time to charge the bootstrap capacitor. And that is, during this period: the minimum on pulse width of low-side MOSFET or the minimum off pulse width of high-side MOSFET, the bootstrap capacitor has to be charged. The recommended value for R_{bs} is 20Ω [28, 29].

6.4.2.2. Overview of the circuit

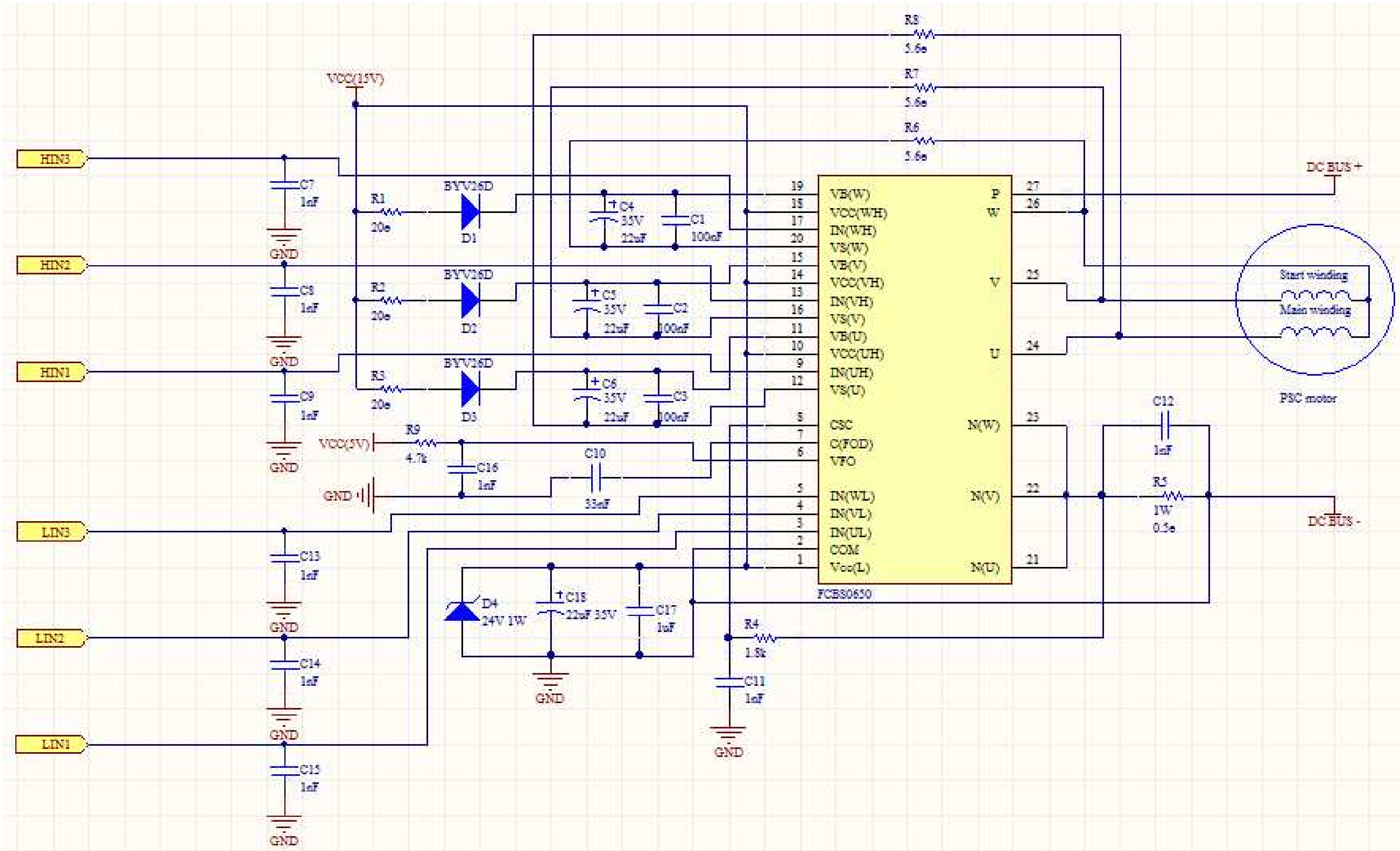

Figure 6.37 Overview of the circuit

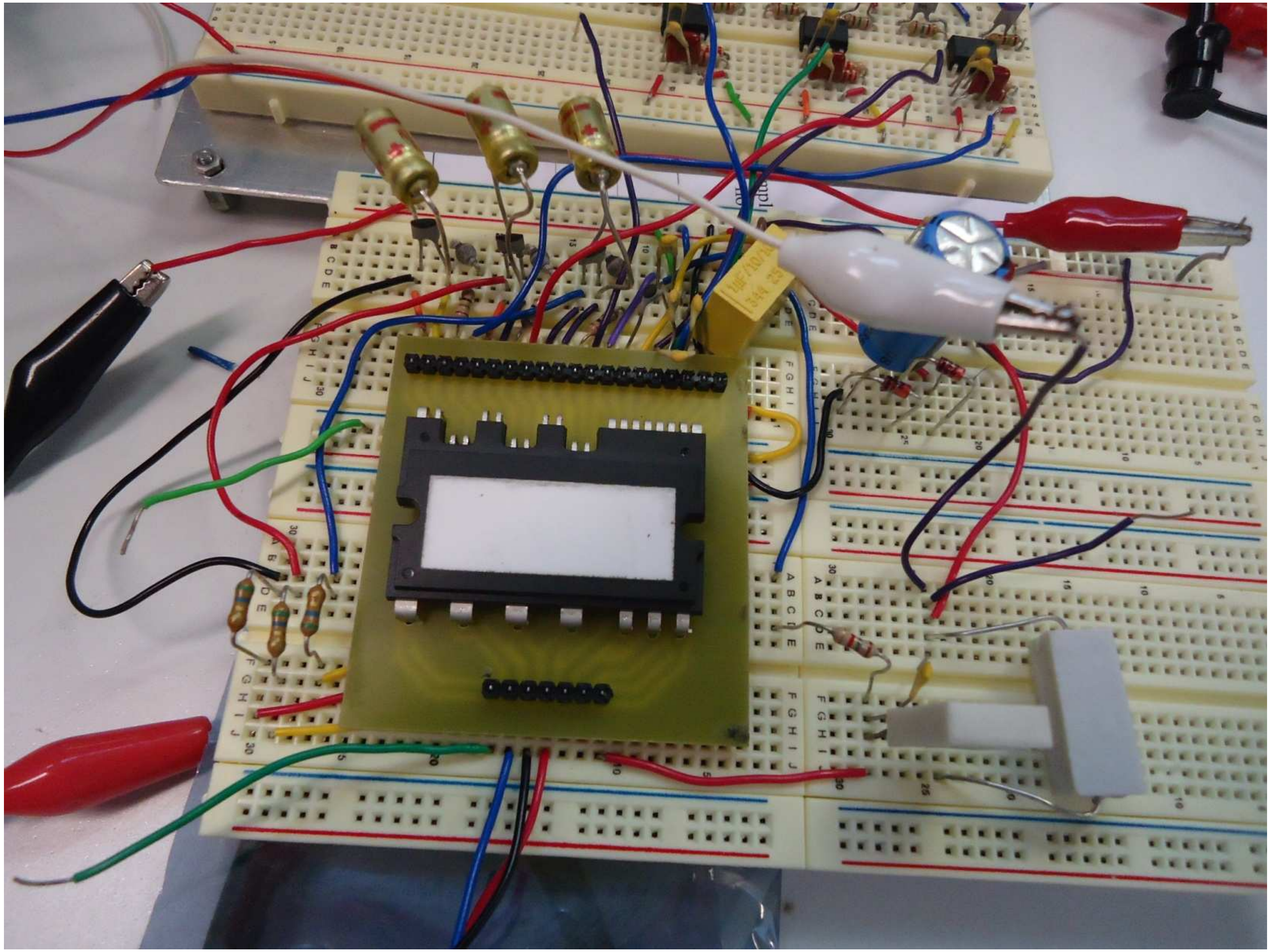

Figure 6.38 Implementation of the circuit

Chapter 7: Conclusions

This thesis has been about speed control of small domestic AC motors which will be used for home automation applications, this means that the best choice is single-phase motor; because in the domestic environments only have single-phase power available.

Our literature study has led us to choose a Permanent Split Capacitor (PSC) motor because of the following reasons:

1. It is the single-phase induction motor that makes the less noise.
2. Excellent for applications with high on/off cycle rates.
3. The most reliable of the single-phase motors.
4. The best choice for variable speed control.
5. It is the one that we had in the laboratory.

I have studied different techniques and drive topologies to control the speed of a PSC motor in one and two directions.

Each control technique has advantages and disadvantages which effect in the selection of the control method. The voltage control technique has a simple structure, is easy to control and is low cost. This technique is based on varying the slip rate. The increase in the slip rate causes the speed to decrease. A major drawback is the increasing stator currents which lead to more copper loss and machine heating.

It is necessary in motor drives to apply a continuous current to the motor in order to protect the motor from electromagnetic moment pulsations and speed oscillations. Motors having high inertia may be harmed from these oscillations.

The *integral cycle control* is based on supplying and cutting the supply currents, leading to discontinuities in the motor current which is a disadvantage in using this control method. This problem can be improved by increasing the total on and off time. One other effect of discontinuing currents in *integral cycle control* is that each control cycle the stator voltage is reduced to zero and again increased to the supply voltage value which increases the transient effects of the motor which is not desired.

In *phase control*, the motor current is much more continuous compared to the integral cycle control, but still has discontinuity.

In *constant V/f* control the motor currents are nearly pure sinusoidal with very small harmonics. This result brings an advantage to this control method compared with phase and integral cycle control.

The integral cycle control and phase control produce very high harmonic content in both motor and supply current waveforms. The effects of these are low efficiency of the drive and transmission lines, acoustic noise and electromagnetic interference. The high harmonic pollution does not comply with strict European EMI/EMC regulations.

As it was said above, the main advantage of V/f control topology is the ability to generate both the amplitude and frequency of the output voltage independently. Another advantage is the harmonic reduction, due to symmetric properties and how the switches are turned on and off; the harmonics are reduced at the output and provide a continuous current to the motor. This topology has one disadvantage; it is the higher cost than the voltage control topologies. It requires numerous active and passive components.

Most PSC motors are designed to run in one direction. However, many applications call for bidirectional motor rotation, as our application does. Gear mechanisms or external relays and switches are used to achieve bidirectional rotation. When mechanical gears are used, the motor shaft runs in one direction and the gears for forward and reverse engage and disengage according to the direction required. Using a microcontroller-based system, you can control the speed but also the direction of rotation can be also changed, based on an algorithm. In addition, there is another disadvantage because the increased capacitor reactance at low frequency tends to drastically reduce the influence of the start winding. Therefore, the pulsation torque increases once the frequency drops, leading to vibrations and higher audible noise.

Using a microcontroller it is possible to generate 90 degrees phase between main and start windings, which means that the big capacitor can be removed, thus reducing the total system cost.

About bidirectional control, there are two methods: *H-bridge* or *Three-phase bridge*. The *H-bridge* is a good V/f control but it has following disadvantages:

- The common point of the windings is directly connected to the neutral power supply. This may increase the switching signals creeping into the main power supply and it may increase the noise. In turn, this may limit the EMI level of the product, violating certain design goals and regulations.

- The effective DC voltage handled is relatively high due to the input-voltage doubler circuit. Moreover, the cost of the voltage doubler circuit itself is high due to two large power capacitors.

A better solution to minimize these problems would be to use a *three-phase inverter bridge*. With this technique the control becomes more efficient, but the control algorithm becomes more complex. In addition, all devices have the same voltage-stress level, which means longer service life.

Our final conclusion is that controlling a PSC motor using a *three-phase inverter* topology provides the best results, such as power efficiency, longer life, lower power dissipation, lower EMI level, reduced audible noise, better control over the application and lower overall system cost

For our proof of concept we have built several test-circuits and made an embedded PWM software implementation. We have implemented a first fast trial based on a 555 Timer Chip and a displacement register. The advantages of this circuit are the simplicity, low cost and the availability these components. On the other hand, this analog technique has less flexibility than using a microcontroller because; the entire system is analog and is hard to change.

The second implementation is based on a microcontroller which can be programmed such that is becomes possible to control a lot of things besides the speed of the motor, for example: perform lower priority tasks, such as diagnostics, self-test, start-up and shutdown sequencing and fault monitoring. About this method, there are two ways to generate PWM, hardware PWM and software PWM and they are both complex. But the software PWM is a little bit easier than hardware PWM. The selected microcontroller to generate software PWM waves is the PIC16F72 because it is one of the simplest and low cost general purpose microcontrollers of Microchip.

The first selection for the inverter was based on MOSFETs and a MOSFET driver. Because the MOSFETs are cheaper, low switching losses, good for low power applications and good performance at high frequency. MOSFET driver is required because is the best way to manage MOSFETs and also has certain protection schemes and blocking signals to help the operation of the motor.

The difficulty in using discrete components is that they can easily get shorted and causing them to burn out. The last implementation to avoid such problems is based on an integrated chip FCBS0650 of Fairchild Semiconductor, which combines the MOSFETs bridge and the MOSFETs driver.

The implementation of this circuit with the chip FCBS0650, verified motor operation in both directions and the variation of speed. Despite it is not working perfectly and in spite of the difficulty of hardware implementation was verified that the theory works and that the motor generates practically no noise. It is possible that the use of old protoboard would lead to bad connections causing the microprocessor failure, generating the sending of erroneous PWM signal causing the malfunction of the inverter module and consequently the motor. It is needed the realization of a PCB board for this circuit to avoid such mistakes and to continue to check the motor noise generation while controlling both the speed and direction.

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Annex A: Soft-Starters

Soft starters are the ideal solution for all problems related to the direct start of an AC motor, such as:

- High startup often represents an unacceptable load on the mains.
- Sudden shocks in gears and other transmission elements that cause wear unnecessary mechanical parts.
- High values of acceleration and deceleration, which originate unstable situations in industrial processes, e.g. in conveyors.

Traditionally, star-delta starters and autotransformer are considered valid solutions to these problems. However, both options have drawbacks and none of them solves any problems due to wear and tear on drive components and the unstable conditions of the processes.

STAR-DELTA STARTERS

It's not possible to implement it in single-phase devices.

AUTOTRANSFORMERS

Reduce the start current and allows some control of this current level. However, autotransformer starters do not eliminate the risk of a sharp increase torque by changing the voltage.

A.1: Soft-Starters

Unlike traditional solutions, the soft starters offer a large number of benefits for motor performance and the team as a whole, among which I mentioned.

- Flexible control of current and torque.
- Soft Control current and voltage, without steep slopes or transitional periods.
- Ability to perform frequent operations start / stop without causing mechanics damages.
- Flexibility to changes in starting conditions, thus increasing also flexibility in implementation.
- Control of braking to reduce or extend the time taken by the motor.

OPERATING PRINCIPLE

The motor voltage is controlled by a principle of phases cutting. Generally, two thyristors in each phase perform power switching, which allows the starter can handle high torques operations and frequent start / stop. There are two ways to control soft starters, which will be explained below.

OPEN LOOP CONTROL

Open Loop soft starters are soft starters producing a start voltage profile which is independent of the current drawn, or the speed of the motor. The start voltage profile is programmed to follow a predetermined contour against time. A very basic timed voltage ramp system operates by applying an initial voltage to the motor and causing this voltage to slowly ramp up to full voltage. Commonly the voltage ramps time is referred to as the acceleration ramp time and is calibrated in seconds.

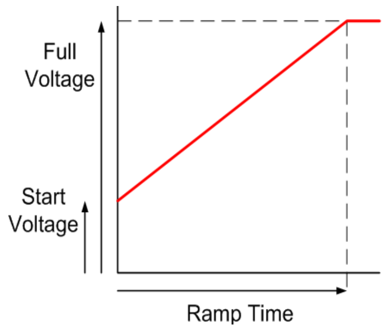

Figure A.1 Open loop control

CLOSED LOOP CONTROL

Closed Loop starters monitor an output characteristic or effect from the starting action and dynamically modify the start voltage profile to cause the desired response. The most common closed loop soft starter is the controlled current soft starter where the current drawn by the motor during start is monitored and controlled to give either a constant current, or a current ramp soft start. A much rarer closed loop format is the constant acceleration soft-start where the motor speed is monitored by a shaft encoder and the voltage is controlled to maintain a constant rate of acceleration or a linear increase in motor speed. The controlled current soft starters are available with varying levels of sophistication.

STARTING TORQUE

To start a machine, the motor must develop sufficient torque over the entire speed range to exceed the work and loss torque of the driven load and provide a surplus torque for accelerating the machine to full speed. The starting torque delivered by the motor at any speed, is equal to the full voltage starting torque at that speed, multiplied by the current or voltage reduction squared. Provided the full voltage speed/torque curves and the full voltage speed/current curves are available, the reduced voltage (or current) speed/torque curves can be calculated. This curve can be superimposed onto the load speed torque curve and provided the torque developed at all speeds exceeds the load torque, the motor will accelerate to full speed. If the curves cross, the start current (or voltage) will need to be increased to increase the start torque developed by the motor. The difference between the torque developed and the load torque is essentially the acceleration torque that will accelerate the machine to full speed.

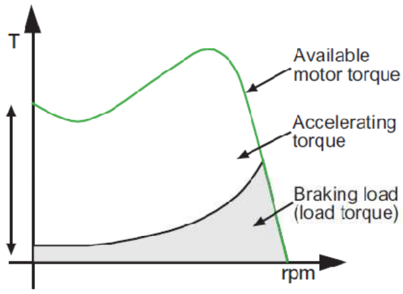

Figure A.2 Starting Torque

SOFT STOP

Soft starters can have soft stop included for no extra cost. The voltage is gradually reduced, reducing the torque capacity of the motor. The reduction of available torque causes the motor to begin to stall when the shaft torque of the motor is less than the torque that is required by the load. As the torque is reduced, the speed of the load will reduce to the point where the load torque equals the shaft torque. Typically, the soft stop used is an open loop voltage ramp, but there are some torque control soft stop systems that use torque feedback to provide better control over the deceleration of the motor.

A.2: Conclusion

Obviously, soft starters offer a lot of advantages and it would be interesting to apply to our project. Due to the use of the microcontroller, the easiest way to obtain soft starts and stops in our motor is by programming the microcontroller.

Annex B: PIC Code

MC_16F72.inc

```
;USER DEFINED VARIABLES
		INCLUDE			<P16F72.INC>
;-------------------------------------------------------------------------------------
;OSCILLATOR FREQUENCY
#DEFINE OSCILLATOR		D'20000000'
;-------------------------------------------------------------------------------------
;TIMER0 PRESCALER
#DEFINE	TIMER0_PRESCALE		D'128'
;-------------------------------------------------------------------------------------
;NUMBER OF ENTRIES IN THE SINE TABLE, OR THE SAMPLING FREQUENCY
#DEFINE	SINE_TABLE_ENTRIES	D'19'
;-------------------------------------------------------------------------------------
;PORT AND BIT DEFINITIONS
#define KEY_PORT		PORTB
#define	RUN_STOP_KEY 0
#define FWD_REV_KEY	1
#define LED_RUN		2
#define LED_DELAY 4
#define LED_STOP 6
#define LED_FWD		3
#define LED_REV		5
#define DEBOUNCE_COUNT 0x80

;BIT DEFINITION OF FLAGS
#DEFINE	MOTOR_FREQ_COUNTER	0
#DEFINE OFFSET1_FLAG	1
#DEFINE OFFSET2_FLAG	2
#DEFINE OFFSET3_FLAG	3

;BIT DEFINITION OF FLAGS1
#define RUN_STOP		0
#define FWD_REV		1
#define DEBOUNCE		2
#define KEY_RS		4
#define KEY_FR		5
#define KEY_PRESSED	6

;BIT DEFINITION OF FLAGS3
#define	PWM_FIRST	0
#define	PWM_SECOND1
#define	PWM_THIRD	3
#define	PWM_NEW_CYCLE4
#DEFINE	DELAY_COUNT1		0XFF
#DEFINE	DELAY_COUNT2		0XFF
#define	PWM_PORT PORTC
#define	PWM0_PIN	0
#define	PWM1_PIN	1
#define	PWM2_PIN	2
#define	PWM3_PIN	3
#define	PWM4_PIN	4
#define	PWM5_PIN	5
;----------------------------------------------------------------
W_TEMP			equ 0x20		;LOCATION FOR SAVING 'WREG' DURING INTERRUPT
STATUS_TEMP		equ 0x21		;LOCATION FOR SAVING 'STATUS' DURING INTERRUPT
FLAGS			equ 0x22		;FLAGS REGISTERS USED TO INDICATE DIFFERENT STATUS
FLAGS1			equ 0x23		;FLAGS REGISTERS USED TO INDICATE DIFFERENT STATUS
FLAGS3			equ 0x25		;FLAGS REGISTERS USED TO INDICATE DIFFERENT STATUS
TEMP_LOC		equ 0x26		;GENERAL PURPOSE TEMPORARY LOCATION
TEMP_LOC_1		equ 0x27		;GENERAL PURPOSE TEMPORARY LOCATION
TEMP_LOC_2		equ 0x28		;GENERAL PURPOSE TEMPORARY LOCATION
NO_1_LSB		equ 0x29		;NUMERATOR(LSB) AND QUOTIENT(LSB) OR MULTIPLIER(LSB)
RESULT_LSB		equ 0x2A		;RESULT OF MULTIPLICATION(LSB)/REMAINDER(LSB)
RESULT_MSB		equ 0x2B		;RESULT OF MULTIPLICATION(MSB)/REMAINDER(MSB)
NEW_FREQ		equ 0x2D		;NEW REFERENCE FREQUENCY INPUT
MOTOR_FREQUENCY		equ 0x2E		;TEMPORARY LOCATION FOR HOLDING DEC_COUNTER OR ACC_COUNTER
TABLE_OFFSET1		equ 0x2F		;PHASE1 OFFSET TO THE SINE TABLE
TABLE_OFFSET2		equ 0x30		;PHASE2 OFFSET TO THE SINE TABLE
TABLE_OFFSET3		equ 0x31		;PHASE3 OFFSET TO THE SINE TABLE
SINE_TABLE_RAM		equ0X32			;SINE TABLE, 0x14 bytes
PWM_PR_CH1_Buff		equ 0x50		;Priority definition on channels
PWM_PR_CH2_Buff		equ 0x51
PWM_PR_CH3_Buff		equ 0x52
PWM1_DS_Buff		equ 0x53		;Duty cycle buffers
PWM2_DS_Buff		equ 0x54
PWM3_DS_Buff		equ 0x55
PWM4_DS_Buff		equ 0x56
DEBOUNCE_COUNTER equ 0x58
;***********************************************************************
```

MC_16F72.asm

```
;----------------------------------------------------------------
;This program is used to control the speed of a Permanent Series Capacitor(PSC) motor
;by using six outputs pins and Timer0 and Timer1 interruptions to
;generate 6PWM waveform.
;Microcontroller used: PIC16F72
;----------------------------------------------------------------
;Author: Padmaraja Yedamale by Appliance Solutions Group
```

```
;Modifications: Iñigo Romo
;Original Update: 20/05/04
;Last Update: 25/05/11
;-----------------------------------------------------------------
        INCLUDE             <MC_16F72.INC>
;-----------------------------------------------------------------
;Configuration bits definition
;Oscillator             : HS
;Watchdog timer         : off
;Power up timer         : on
;Brown out detect       : on
;Code protect  :off
        __CONFIG 0x2012
;-----------------------------------------------------------------
;Macro
MULT   MACRO  BIT               ;MACRO FOR UNSIGNEDMULTIPLICATION
        btfsc  NO_1_LSB,BIT
        addwf  RESULT_MSB,F
        RRF    RESULT_MSB,F
        RRF    RESULT_LSB,F
        ENDM                            ;END OF MACRO FOR MULTIPLICATION

;-----------------------------------------------------------------
STARTUP     CODE      0X00              ;RESET VECTOR ADDRESS
            goto      START

            CODE      0X04              ;INTERRUPT VECTOR LOCATION
            goto      ISR_INT           ;goto INTERRUPT SERVICE ROUTINE

;*****************************************************************
PROG        CODE
START
;*****************************************************************
;INITIALIZATION OF THE PORTS AND TIMERS
            bsf                 STATUS,RP0
            movlw     0X03
            movwf     TRISB             ;RB0-1 AND CONFIGURED AS INPUT
            movlw     0X00
            movwf     TRISC             ;RC0-RC7 CONFIGURED AS OUTPUT
            bcf       STATUS,RP0
            movlw     b'00111111'       ; TURN OFF PWM
            movwf     PWM_PORT
            clrf      PWM_PR_CH1_Buff
            clrf      PWM_PR_CH2_Buff
            clrf      PWM_PR_CH3_Buff
            clrf      PWM1_DS_Buff
            clrf      PWM2_DS_Buff
            clrf      PWM3_DS_Buff
            clrf      PWM4_DS_Buff
            clrf      FLAGS             ;CLEAR ALL FLAGS
            clrf      FLAGS1            ;CLEAR ALL FLAGS
            clrf      FLAGS3            ;CLEAR ALL FLAGS
            call      STOP_MOTOR;STOP MOTOR
            call      COPY_TABLE_TO_RAM ;COPY SINE TABLE FROM PROGRAM MEMORY TO RAM FOR FASTER ACCESS
;*******************************************************************
;INITIALIZE ADC REGISTERS
;*******************************************************************
            bcf       STATUS,RP0
            movlw     b'10000001'
            movwf     ADCON0            ;CONFIGURE FOR 32TOSC AND CHANNEL FOR CONVERSION - RA0 (FREQUENCY)
            bsf       STATUS,RP0
            movlw     b'00000010'       ;CONFIGURE RA0-RA4 AS ANALOG INPUT
            movwf     ADCON1
            movlw     b'00001111'       ;RA0-RA3 INPUT and RA4-RA7 OUTPUT
            movwf     TRISA
            bcf       STATUS,RP0
;*******************************************************************
;TIMER1 INITIALIZATION WITH PRESCALER - USED FOR SETTING THE PWM TIMING
;*******************************************************************
            movlw     b'00100001'                   ;LOAD THE T1CON WITH CONTROL WORD
            movwf     T1CON                                   ;FOR TMR1 ON AND PRESCALAR IS 1:4, INTERNAL CLOCK
;*******************************************************************
;TIMER0 INITIALIZATION WITH PRESCALER - USED FOR ACCELERATION,DECELERATION AND ADC TRIGGER FOR FREQ. CONV.
;*******************************************************************
            bsf                 STATUS,RP0
            movlw     b'10000110'                             ;prescale 1:128
            movwf     OPTION_REG
            bcf                 STATUS,RP0
            clrf      INTCON                                  ;DISABLE ALL INTERRUPTS AND FLAGS ASSOCIATED WITH
            clrf      PIR1                                    ;DISABLE ALL INTERRUPT FLAGS
            bsf                 STATUS,RP0
            clrf      PIE1                                    ;DISABLE ALL INTERRUPTS
            movlw     0X03                                    ;SET #POR AND #BOR FLAGS
            movwf     PCON
            bcf                 STATUS,RP0
            clrf      KEY_PORT
;---------
            bsf                 KEY_PORT,LED_STOP
WAIT_HERE
            btfss     KEY_PORT,RUN_STOP_KEY
            goto      WAIT_HERE
;***********************************************************************
            bsf                 FLAGS1,RUN_STOP
```

```
		bcf			KEY_PORT,LED_STOP
		bsf			KEY_PORT,LED_DELAY
		call		BIG_DELAY
;*******************************************************************************
		call		RUN_MOTOR_AGAIN
		movlw		0xb4
		movwf		NEW_FREQ
		call		UPDATE_PWM_DUTYCYCLES	;UPDATE THE PWM DUTY CYCLE WITH NEW VALUE
		call		PRIORATIZE_PWMS
		call		CALCULATE_NEW_SPEED
		bcf		STATUS,RP0
		bsf		INTCON,INTE			;ENABLE RB PORT CHANGE INTERRUPT FOR RB4
		bsf		INTCON,PEIE			;PERIPHERAL INTERRUPTS ENABLE
		bsf		INTCON,GIE				;GLOBAL INTERRUPT ENABLE
		bsf		PIE1,ADIE

;*************************************************************************
;MAIN LOOP, THE PROGRAM WILL BE LOOPING
;*************************************************************************
MAIN_LOOP
		btfss		FLAGS,MOTOR_FREQ_COUNTER
		goto		BYPASS
		bcf		FLAGS,MOTOR_FREQ_COUNTER		;CLEAR TMR0 OV FLAG
		call		UPDATE_PWM_DUTYCYCLES		;YES, UPDATE THE PWM DUTY CYCLE WITH NEW VALUE
		call		PRIORATIZE_PWMS
		call		UPDATE_TABLE_OFFSET			;UPDATE 3 OFFSETS
		call		CALCULATE_NEW_SPEED
		btfss		ADCON0, GO				;If AD Conversion is complete
		bsf			ADCON0, GO			;		then start a new conversion
BYPASS
		btfsc		PIR1,ADIF				;ADC CONVERSION COMPLETE INTERRUPT?
		call		AD_CONV_COMPLETE			;YES - CONVERSON RESULT 'F - MOTOR FREQUENCY'

		call		KEY_CHECK				;CHECK KEYS CHANGE
		call		PROCESS_KEY_PRESSED
		goto		MAIN_LOOP				;GO BACK TO MAIN LOOP
;*************************************************************************
;INTERRUPT SERVICE ROUTINE
;*************************************************************************
ISR_INT
		movwf		W_TEMP				;COPY W TO A TEMPORARY REGISTER
		swapf		STATUS,W			;SWAP STATUS NIBBLES AND PLACE INTO W REGISTER
		movwf		STATUS_TEMP			;SAVE STATUS TO A TEMPORARY REGISTER IN BANK0
		bcf			STATUS,RP0
		btfsc		PIR1,TMR1IF		;TIMER1 OVERFLOW INTERRUPT?
		goto		TIMER1_OVERFLOW		;YES - INTERRUPT FOR UPDATING TMR1 REGISTERS BASED ON POT SETTING
		btfsc		INTCON,T0IF		;TIMER0 OVERFLOW INTERRUPT?
		goto		TIMER0_OVERFLOW		;YES - INTERRUPT FOR UPDATING TMR0 REGISTERS BASED ON POT SETTING
POPUP							;RETRIEVE SAVED WREG AND STAUS REGISTER VALUES
		swapf STATUS_TEMP,W			;SWAP ORIGINAL STATUS REGISTER VALUE INTO W (RESTORES ORIGINAL BANK)
		movwf STATUS				;RESTORE STATUS REGISTER FROM W REGISTER
		swapf W_TEMP,F				;SWAP W_TEMP NIBBLES AND RETURN VALUE TO W_TEMP
		swapf W_TEMP,W				;SWAP W_TEMP TO W TO RESTORE ORIGINAL W VALUE WITHOUT AFFECTING STATUS
		RETFIE					;RETURN FROM INTERRUPT
;*************************************************************************
TIMER1_OVERFLOW						;TMR1 OVERFLOW ISR
		bcf		PIR1,TMR1IF		;CLEAR TMR1IF
;---
		btfss		FLAGS3,PWM_FIRST
		goto		TAKE_CARE_PWM_SECOND
		btfsc		PWM_PR_CH1_Buff,0
		bsf			PWM_PORT,PWM1_PIN	;PWM1 is turn off
		btfsc		PWM_PR_CH1_Buff,1
		bsf			PWM_PORT,PWM3_PIN	;PWM3 is turn off
		btfsc		PWM_PR_CH1_Buff,2
		bsf			PWM_PORT,PWM5_PIN	;PWM5 is turn off
		btfsc		PWM_PR_CH1_Buff,0
		bcf			PWM_PORT,PWM0_PIN	;PWM0 is turn on
		btfsc		PWM_PR_CH1_Buff,1
		bcf			PWM_PORT,PWM2_PIN	;PWM2 is turn on
		btfsc		PWM_PR_CH1_Buff,2
		bcf			PWM_PORT,PWM4_PIN	;PWM4 is turn on
		bcf			FLAGS3,PWM_FIRST
		movlw		0xFF
		movwf		TMR1H
		bsf			FLAGS3,PWM_SECOND
		comf		PWM2_DS_Buff,W
		movwf		TMR1L
		btfss		STATUS,Z
		goto		POPUP
;---
TAKE_CARE_PWM_SECOND
		btfss		FLAGS3,PWM_SECOND
		goto		TAKE_CARE_PWM_THIRD
		btfsc		PWM_PR_CH2_Buff,0
		bsf			PWM_PORT,PWM1_PIN	;PWM1 is turn off
		btfsc		PWM_PR_CH2_Buff,1
		bsf			PWM_PORT,PWM3_PIN	;PWM3 is turn off
		btfsc		PWM_PR_CH2_Buff,2
		bsf			PWM_PORT,PWM5_PIN	;PWM5 is turn off
		btfsc		PWM_PR_CH2_Buff,0
		bcf			PWM_PORT,PWM0_PIN	;PWM0 is turn on
		btfsc		PWM_PR_CH2_Buff,1
```

```
		bcf		PWM_PORT,PWM2_PIN	;PWM2 is turn on
		btfsc	PWM_PR_CH2_Buff,2
		bcf		PWM_PORT,PWM4_PIN	;PWM4 is turn on
		bcf		FLAGS3,PWM_SECOND
		movlw	0xFF
		movwf	TMR1H
		bsf		FLAGS3,PWM_THIRD
		comf	PWM3_DS_Buff,W
		movwf	TMR1L
		btfss	STATUS,Z
		goto	POPUP
;---
TAKE_CARE_PWM_THIRD
		btfss	FLAGS3,PWM_THIRD
		goto	TAKE_CARE_FOR_NEXT_CYCLE
		btfsc	PWM_PR_CH3_Buff,0
		bsf		PWM_PORT,PWM1_PIN	;PWM1 is turn off
		btfsc	PWM_PR_CH3_Buff,1
		bsf		PWM_PORT,PWM3_PIN	;PWM3 is turn off
		btfsc	PWM_PR_CH3_Buff,2
		bsf		PWM_PORT,PWM5_PIN	;PWM5 is turn off
		btfsc	PWM_PR_CH3_Buff,0
		bcf		PWM_PORT,PWM0_PIN	;PWM0 is turn on
		btfsc	PWM_PR_CH3_Buff,1
		bcf		PWM_PORT,PWM2_PIN	;PWM2 is turn on
		btfsc	PWM_PR_CH3_Buff,2
		bcf		PWM_PORT,PWM4_PIN	;PWM4 is turn on
		bcf		FLAGS3,PWM_THIRD
		movlw	0xFF
		movwf	TMR1H
		bsf		FLAGS3,PWM_NEW_CYCLE
		comf	PWM4_DS_Buff,W
		movwf	TMR1L
		btfss	STATUS,Z
		goto	POPUP
;---
TAKE_CARE_FOR_NEXT_CYCLE
		movlw	b'00111111'	;Turn off all PWMs(active low)
		movwf	PWM_PORT
		comf	PWM1_DS_Buff,W
		movwf	TMR1L
		movlw	0xFF
		movwf	TMR1H
		bcf		FLAGS3,PWM_NEW_CYCLE
		bsf		FLAGS3,PWM_FIRST
		movlw	b'00010101'		;Turn on PWM1,3,5 PWMs(active low) at the beginning of the cycle
		movwf	PWM_PORT
		goto	POPUP
;******************************************************************
TIMER0_OVERFLOW								;TMR0 overflow ISR
		movf	MOTOR_FREQUENCY,W
		movwf	TMR0
		bsf		FLAGS,MOTOR_FREQ_COUNTER
		bcf		INTCON,T0IF			;Clear T0IF
		goto	POPUP
;*****************************************************************
AD_CONV_COMPLETE						;ADC INTERRUPT
		bcf		PIR1,ADIF			;ADIF FLAG IS CLEARED FOR NEXT INTERRUPT
		movf	ADRES,W				;READ AD CONVERSION RESULT
		movwf	NEW_FREQ			;CHECK FOR LOWER AND UPPER ALLOWED LIMIT OF FREQ.
		sublw	0x14				;MINIMUM FREQUENCY SET TO 5HZ (SCALING FACTOR X4)
		btfss	STATUS,C			;IS POT SETTING FOR FREQ, MORE THAT LOWER SET LIMIT?
		goto	CHECK_UPPER_LIMIT_FREQUENCY	;YES - NOW CHECK UPPER LIMIT
		movlw	0x14				;NO - SET FREQ. TO LOWER ALLOWED LIMIT - 5HZ (X4)
		movwf	NEW_FREQ
		return
CHECK_UPPER_LIMIT_FREQUENCY
		movlw	0xD0
		subwf	NEW_FREQ,W
		btfss	STATUS,C			;IS POT SETTING MORE THAN ALLOWED UPPER LIMIT OF FREQ?
		return							;NO - RETURN FROM INTERRUPT
		movlw	0xD0					;YES - SET FREQ TO UPPER ALLOWED LIMIT - 58HZ (X4)
		movwf	NEW_FREQ
		return
;************************************************************************
;THIS ROUTINE WILL UPDATE THE PWM DUTY CYCLE ACCORDING TO THE OFFSET TO THE TABLE
;THIS ROUTINE SCALES THE PWM VALUE FROM THE TABLE BASED ON THE FREQUENCY TO KEEP V/F
;CONSTANT AND LOADS THEM IN APPROPRIATE  REGISTER DEPENDING ON SETTING
;************************************************************************
UPDATE_PWM_DUTYCYCLES
		movlw	LOW		SINE_TABLE_RAM
		movwf	FSR						;BASE ADDRESS OF SINE TABLE IN RAM IS LOADED TO FSR
		movf	TABLE_OFFSET1,W			;TABLE_OFFSET1 IS COPIED TO WREG
		addwf	FSR,F					;ADRESS TO BE READ=SINE TABLE BASE ADRESS + TABLE_OFFSET1
		BANKISEL	SINE_TABLE_RAM
		movf	INDF,W					;COPY SINE TABLE VALUE, POINTED BY FSR, TO WREG
		btfsc	STATUS,Z			;CHECK IS VALUE READ ZERO?
		goto	PWM1_IS_0			;YES, goto PWM1_IS_0
		movwf	NO_1_LSB			;NO, SINE TABEL VALUE X SET_FREQ TO SCALE TABLE VALUE BASED ON FREQUENCY SETTING
		call	MUL_8X8					;CALL ROUTINE FOR UNSIGNED 8x8 BIT MULTIPLICATION
		movf	RESULT_MSB,W			;8 MSB OF 16 BIT RESULT IS STORED
		movwf	TEMP_LOC			;AT TEMP_LOC - THIS REPRESENT PWM DUTY CYCLE VALUE FOR PHASE 1
		goto	UPDATE_PWM2				;GO FOR UPDATING PWM DUTY CYCLE FOR 2ND PHASE
```

```
PWM1_IS_0
        clrf        TEMP_LOC                    ;CLEAR PWM DUTY CYCLE VALUE FOR PHASE 1

UPDATE_PWM2
        movlw       LOW     (SINE_TABLE_RAM)
        movwf       FSR                                 ;BASE ADDRESS OF SINE TABLE IN RAM IS LOADED TO FSR
        movf        TABLE_OFFSET2,W                     ;TABLE_OFFSET2 IS COPIED TO WREG
        addwf       FSR,F                               ;ADRESS TO BE READ=SINE TABLE BASE ADRESS + TABLE_OFFSET2
        BANKISEL    SINE_TABLE_RAM
        movf        INDF,W                              ;COPY SINE TABLE VALUE, POINTED BY FSR, TO WREG
        btfsc       STATUS,Z                    ;CHECK IS VALUE READ ZERO?
        goto        PWM2_IS_0                   ;YES, goto PWM2_IS_0
        movwf       NO_1_LSB                    ;NO, SINE TABEL VALUE X SET_FREQ TO SCALE TABLE VALUE BASED ON FREQUENCY SETTING
        call        MUL_8X8                             ;CALL ROUTINE FOR UNSIGNED 8x8 BIT MULTIPLICATION
        movf        RESULT_MSB,W                        ;8 MSB OF 16 BIT RESULT IS STORED
        movwf       TEMP_LOC_1                  ;AT TEMP_LOC_1 - THIS REPRESENT PWM DUTY CYCLE VALUE FOR PHASE 2
        goto        UPDATE_PWM3                         ;GO FOR UPDATING PWM DUTY CYCLE FOR 3RD PHASE

PWM2_IS_0
        clrf        TEMP_LOC_1                  ;CLEAR PWM DUTY CYCLE VALUE FOR PHASE 2

UPDATE_PWM3
        movlw       LOW     SINE_TABLE_RAM
        movwf       FSR                                 ;BASE ADDRESS OF SINE TABLE IN RAM IS LOADED TO FSR
        BANKSEL     TABLE_OFFSET3
        movf        TABLE_OFFSET3,W                     ;TABLE_OFFSET3 IS COPIED TO WREG
        addwf       FSR,F                               ;ADRESS TO BE READ=SINE TABLE BASE ADRESS + TABLE_OFFSET3
        BANKISEL    SINE_TABLE_RAM
        movf        INDF,W                              ;COPY SINE TABLE VALUE, POINTED BY FSR, TO WREG
        btfsc       STATUS,Z                    ;CHECK IS VALUE READ ZERO?
        goto        PWM3_IS_0                   ;YES, goto PWM3_IS_0
        movwf       NO_1_LSB                    ;NO, SINE TABEL VALUE X SET_FREQ TO SCALE TABLE VALUE BASED ON FREQUENCY SETTING
        call        MUL_8X8                             ;CALL ROUTINE FOR UNSIGNED 8x8 BIT MULTIPLICATION
        movf        RESULT_MSB,W                        ;8 MSB OF 16 BIT RESULT IS STORED
        movwf       TEMP_LOC_2                  ;AT TEMP_LOC_2 - THIS REPRESENT PWM DUTY CYCLE VALUE FOR PHASE 3
        goto        SET_PWM12                   ;GO FOR CHECKING DIRECTION OF MOTOR ROTATION REEQUIRED

PWM3_IS_0
        clrf        TEMP_LOC_2                  ;CLEAR PWM DUTY CYCLE VALUE FOR PHASE 3
SET_PWM12
        movf        TEMP_LOC,W
        movwf       PWM1_DS_Buff
        movf        TEMP_LOC_1,W
        movwf       PWM2_DS_Buff
        movf        TEMP_LOC_2,W
        movwf       PWM3_DS_Buff
        RETURN

;*******************************************************************************
;THIS ROUTINE UPDATES THE OFFSET POINTERS TO THE TABLE AFTER EVERY ACCESS
;*******************************************************************************
UPDATE_TABLE_OFFSET
        bcf                 STATUS,RP0
        btfss       FLAGS,OFFSET1_FLAG          ;IF SET INCR. ON TABLE
        goto        DECREMENT_OFFSET1
        movlw       (SINE_TABLE_ENTRIES-1)  ;CHECK FOR THE LAST VALUE ON THE TABLE
        SUBWF       TABLE_OFFSET1,W
        btfsc       STATUS,C
        goto        CLEAR_OFFSET1_FLAG
        INCF        TABLE_OFFSET1,F                     ;INCREMENT OFFSET1
        goto        UPDATE_OFFSET2
CLEAR_OFFSET1_FLAG
        bcf         FLAGS,OFFSET1_FLAG
DECREMENT_OFFSET1
        DECFSZ      TABLE_OFFSET1,F                     ;DECREMENT OFFSET1
        goto        UPDATE_OFFSET2
        bsf                 FLAGS,OFFSET1_FLAG
UPDATE_OFFSET2
        btfss       FLAGS,OFFSET2_FLAG          ;IF SET INCR. ON TABLE
        goto        DECREMENT_OFFSET2
        movlw       (SINE_TABLE_ENTRIES-1)      ;CHECK FOR THE LAST VALUE ON THE TABLE
        SUBWF       TABLE_OFFSET2,W
        btfsc       STATUS,C
        goto        CLEAR_OFFSET2_FLAG
        INCF        TABLE_OFFSET2,F                     ;INCREMENT OFFSET2
        goto        UPDATE_OFFSET3
CLEAR_OFFSET2_FLAG
        bcf         FLAGS,OFFSET2_FLAG
DECREMENT_OFFSET2
        DECFSZ      TABLE_OFFSET2,F                     ;DECREMENT OFFSET2
        goto        UPDATE_OFFSET3
        bsf         FLAGS,OFFSET2_FLAG
UPDATE_OFFSET3
        btfss       FLAGS,OFFSET3_FLAG          ;IF SET INCR. ON TABLE
        goto        DECREMENT_OFFSET3
        movlw       (SINE_TABLE_ENTRIES-1)  ;CHECK FOR THE LAST VALUE ON THE TABLE
        SUBWF       TABLE_OFFSET3,W
        btfsc       STATUS,C
        goto        CLEAR_OFFSET3_FLAG
        INCF        TABLE_OFFSET3,F                     ;INCREMENT OFFSET3
        RETURN
CLEAR_OFFSET3_FLAG
        bcf         FLAGS,OFFSET3_FLAG
```

```
DECREMENT_OFFSET3
		DECFSZ		TABLE_OFFSET3,F				;DECREMENT OFFSET3
		RETURN
		bsf		FLAGS,OFFSET3_FLAG
		RETURN
;*****************************************************************************
CALCULATE_NEW_SPEED
		movf		NEW_FREQ,W
		movwf		MOTOR_FREQUENCY
		movlw		.34
		addwf		MOTOR_FREQUENCY,F
		bcf		STATUS,C
		rrf		MOTOR_FREQUENCY,F
		bcf		STATUS,C
		rrf		MOTOR_FREQUENCY,F
		movlw		.181
		addwf		MOTOR_FREQUENCY,F
		return
;************************************************************************
;PWMs are arranged from low duty cycle to high duty cycle
;Original duty cycles are input to routine on PWMx_DS
;Output on PWM_DSx and PWM_PR_CHx
PRIORATIZE_PWMS
		movlw		0x1
		movwf		PWM_PR_CH1_Buff
		movlw		0x2
		movwf		PWM_PR_CH2_Buff
		movlw		0x4
		movwf		PWM_PR_CH3_Buff
		movf		PWM1_DS_Buff,W
		subwf		PWM2_DS_Buff,W
		btfss		STATUS,C
		goto		INTCHG_1_2
		goto		CHECK_2_3
INTCHG_1_2
;interchange duty cycles in 1 and 2
		movf		PWM1_DS_Buff,W
		movwf		TEMP_LOC
		movf		PWM2_DS_Buff,W
		movwf		PWM1_DS_Buff
		movf		TEMP_LOC,W
		movwf		PWM2_DS_Buff
;interchange the PWM outputs
		movf		PWM_PR_CH1_Buff,W
		movwf		TEMP_LOC
		movf		PWM_PR_CH2_Buff,W
		movwf		PWM_PR_CH1_Buff
		movf		TEMP_LOC,W
		movwf		PWM_PR_CH2_Buff
CHECK_2_3
;interchange duty cycles in 2 and 3
		movf		PWM2_DS_Buff,W
		subwf		PWM3_DS_Buff,W
		btfss		STATUS,C
		goto		INTCHG_2_3
		goto		CHECK_1_2_AGN
INTCHG_2_3
		movf		PWM2_DS_Buff,W
		movwf		TEMP_LOC
		movf		PWM3_DS_Buff,W
		movwf		PWM2_DS_Buff
		movf		TEMP_LOC,W
		movwf		PWM3_DS_Buff
;interchange the PWM outputs pins
		movf		PWM_PR_CH2_Buff,W
		movwf		TEMP_LOC
		movf		PWM_PR_CH3_Buff,W
		movwf		PWM_PR_CH2_Buff
		movf		TEMP_LOC,W
		movwf		PWM_PR_CH3_Buff

CHECK_1_2_AGN
;interchange duty cycles in 1 and 2
		movf		PWM1_DS_Buff,W
		subwf		PWM2_DS_Buff,W
		btfss		STATUS,C
		goto		INTCHG_1_2_AGN
		goto		CALCULATE_TIMER_RELOAD
INTCHG_1_2_AGN
		movf		PWM1_DS_Buff,W
		movwf		TEMP_LOC
		movf		PWM2_DS_Buff,W
		movwf		PWM1_DS_Buff
		movf		TEMP_LOC,W
		movwf		PWM2_DS_Buff
;interchange the PWM outputs pins
		movf		PWM_PR_CH1_Buff,W
		movwf		TEMP_LOC
		movf		PWM_PR_CH2_Buff,W
		movwf		PWM_PR_CH1_Buff
		movf		TEMP_LOC,W
		movwf		PWM_PR_CH2_Buff
CALCULATE_TIMER_RELOAD
```

```
        movlw   .156                    ;Corresponding to 8KHz count with Timer1 prescale 1:4
        movwf   PWM4_DS_Buff            ; 156*4=624 instructions
        movf    PWM3_DS_Buff,W
        subwf   PWM4_DS_Buff,F
        movf    PWM2_DS_Buff,W
        subwf   PWM3_DS_Buff,F
        movf    PWM1_DS_Buff,W
        subwf   PWM2_DS_Buff,F

        RETURN
;*******************************************************************************
;This routine checks for the keys status. 2 keys are checked, RUN/STOP and
;Forward(FWD)/Reverse(REV)
;*******************************************************************************
KEY_CHECK
        btfss   KEY_PORT,RUN_STOP_KEY           ;Is key pressed "RUN/STOP"?
        goto    CHECK_FWD_REV_KEY
        btfsc   FLAGS1,DEBOUNCE
        return
        call    KEY_DEBOUNCE
        btfss   FLAGS1,DEBOUNCE
        return
        bsf             FLAGS1,KEY_RS
        return

CHECK_FWD_REV_KEY
        btfss   KEY_PORT,FWD_REV_KEY            ;Is key pressed "FWD/REV"?
        goto    SET_KEYS
        btfsc   FLAGS1,DEBOUNCE
        return
        call    KEY_DEBOUNCE
        btfss   FLAGS1,DEBOUNCE
        return
        bsf             FLAGS1,KEY_FR
        return

SET_KEYS
        btfss   FLAGS1,DEBOUNCE
        return
        bcf             FLAGS1,DEBOUNCE
        bsf             FLAGS1,KEY_PRESSED
        btfss   FLAGS1,KEY_RS
        goto    ITS_FWD_REV
        btfss   FLAGS1,RUN_STOP                         ;Toggle RUN_STOP bit
        goto    $+3
        bcf             FLAGS1,RUN_STOP
        return
        bsf             FLAGS1,RUN_STOP
        return

ITS_FWD_REV
        btfss   FLAGS1,FWD_REV                          ;Toggle FWD_REV bit
        goto    $+3
        bcf             FLAGS1,FWD_REV
        return
        bsf             FLAGS1,FWD_REV
        return

;*******************************************************************************
KEY_DEBOUNCE
        decfsz  DEBOUNCE_COUNTER,F              ;Key debounce time checked
        return
        bsf             FLAGS1,DEBOUNCE
        movlw   DEBOUNCE_COUNT
        movwf   DEBOUNCE_COUNTER
        return
;*******************************************************************************
PROCESS_KEY_PRESSED
        btfss   FLAGS1,KEY_PRESSED                      ;Is there a key press waiting?
        return
        btfss   FLAGS1,KEY_RS                           ;Is it RUN/STOP?
        goto    CHECK_FWD_REV
        btfss   FLAGS1,RUN_STOP                         ;Yes,Was the previous state a Stop?
        goto    STOP_MOTOR_NOW
        bcf     KEY_PORT,LED_STOP
        bsf     KEY_PORT,LED_DELAY
        call    BIG_DELAY                               ;Delay
        call    RUN_MOTOR_AGAIN                         ;Yes, Then RUN the motor
        bcf     FLAGS1,KEY_PRESSED                      ;Clear the Flag
        bcf     FLAGS1,KEY_RS
        return
STOP_MOTOR_NOW
        call    STOP_MOTOR                      ;Was the previous state a RUN?, Then stop the motor
        bcf     FLAGS1,KEY_PRESSED
        bcf     FLAGS1,KEY_RS
        return
CHECK_FWD_REV
        btfss   FLAGS1,KEY_FR                           ;Is the Key pressed = FWD/REV?
        return
        btfss   FLAGS1,RUN_STOP                         ;Was the previous state a Stop?
        bsf     FLAGS1,RUN_STOP
        call    STOP_MOTOR                      ;Stop the motor before reversing
        bcf     KEY_PORT,LED_STOP
```

```
        bcf     KEY_PORT,LED_REV
        bcf     KEY_POT,LED_FWD
        bsf             KEY_PORT,LED_DELAY
        call    BIG_DELAY                       ;Delay between reversing the direction
        call    RUN_MOTOR_AGAIN                 ;Run the motor in Reverse direction
        bcf     FLAGS1,KEY_PRESSED              ;Clear Flags
        bcf     FLAGS1,KEY_FR
        return
;*****************************************************************************
;THIS ROUTINE STOPS THE MOTOR BY DRIVING THE PWMS TO 0% DUTY CYCLE. ALSO DISABLE
;SELECT INTERRUPT TO MAINTAIN STOP CONDITION OF MOTOR
;*****************************************************************************
STOP_MOTOR
        movlw   b'00111111'   ;Turn off all PWMs(active low)
        movwf   PWM_PORT
        bcf     KEY_PORT,LED_RUN
        bsf     KEY_PORT,LED_STOP
        bsf     STATUS,RP0
        bcf     PIE1,TMR1IE ;Disable Timer1 interrupt
        bcf     PIE1,ADIE       ;Disable adc interrupt
        bcf     STATUS,RP0
        bcf     INTCON,T0IE ;Disable Timer0 interrupt
        bcf     FLAGS,MOTOR_FREQ_COUNTER
        clrf    TABLE_OFFSET1
        clrf    TABLE_OFFSET2
        clrf    TABLE_OFFSET3
        RETURN
;*****************************************************************************
;THIS ROUTINE STARTS MOTOR FROM PREVIOUS STOP WITH MOTOR PARAMETERS INITIALIZED
;*****************************************************************************
RUN_MOTOR_AGAIN
        call    INIT_MOTOR_PARAMETERS
        bcf     KEY_PORT,LED_DELAY
        bsf     KEY_PORT,LED_RUN
        bsf     STATUS,RP0
        bsf     PIE1,TMR1IE ; activa la interrupcion del overflow del timer1
;       bsf     PIE1,ADIE
        bcf     STATUS,RP0
        bsf     INTCON,T0IE ;activa la interrupcion del timer0
        RETURN
;*****************************************************************************
;THIS ROUTINE INITIALIZES THE PARAMETERS REQUIRED FOR MOTOR INITIALIZATION.
;*****************************************************************************
INIT_MOTOR_PARAMETERS
        movlw   0X12                            ;INITIALIZE THE TABLE OFFSET TO 3 REGISTERS
        movwf   TABLE_OFFSET1
        movlw   0X00
        movwf   TABLE_OFFSET2
        movlw   0X09
        movwf   TABLE_OFFSET3
        bcf             FLAGS,OFFSET1_FLAG      ;OFFSET FLAGS INITIALIZATION
        bsf             FLAGS,OFFSET2_FLAG
        btfsc   FLAGS1,FWD_REV
        goto    INIT_MOT_REV
        bsf             FLAGS,OFFSET3_FLAG      ;Offset3 initialized
        bcf             KEY_PORT,LED_REV
        bsf             KEY_PORT,LED_FWD
        goto    INIT_MOT_FREQ
INIT_MOT_REV
        bcf             FLAGS,OFFSET3_FLAG
        bcf             KEY_PORT,LED_FWD
        bsf             KEY_PORT,LED_REV
INIT_MOT_FREQ
        movlw   0XB1
        movwf   TMR0
        bsf             FLAGS,MOTOR_FREQ_COUNTER
        RETURN
;*****************************************************************************
;ROUTINE FOR 8*8 BIT MULTIPLICAION ( multiplicacion de dos numeros hasta 255*255)
;*****************************************************************************
MUL_8X8
        clrf   RESULT_MSB
        clrf   RESULT_LSB
        movf   NEW_FREQ,W               ;MOVE THE MULTIPLICAND TO W REG.
        bcf    STATUS,C                 ;CLEAR THE CARRY BIT IN THE STATUS REG.
        MULT   0
        MULT   1
        MULT   2
        MULT   3
        MULT   4
        MULT   5
        MULT   6
        MULT   7
        RETLW  0

;*****************************************************************************
;UPON INITIALIZATION THE SINE TABLE CONTENTS ARE COPIED TO THE RAM FROM
;PROGRAM MEMORY
;*****************************************************************************
COPY_TABLE_TO_RAM
        BANKSEL    SINE_TABLE_RAM
        BANKISEL   SINE_TABLE_RAM
        movlw      LOW SINE_TABLE_RAM
```

```
            movwf       FSR
            movlw       .19
            movwf       TEMP_LOC
            clrf        TEMP_LOC_1
COPY_AGAIN
            movlw       HIGH        SINE_TABLE
            movwf       PCLATH
            movf        TEMP_LOC_1,W
            call        SINE_TABLE
            movwf       INDF
            INCF        TEMP_LOC_1,F
            INCF        FSR,F
            DECFSZ      TEMP_LOC,F
            goto        COPY_AGAIN
            movlw       LOW         SINE_TABLE_RAM              ;FSR POINTS TO THE STARTING OF THE TABLE
            movwf       FSR
            RETURN
;*********************************************************************************
;EQUATION USED FOR CALCULATION OF SINE TABLE ENTRIES = (SIN(ANGLE)+1)*190/2
;Sine table has value corresponding to every 10 electrical degrees
;*********************************************************************************
TABLE       CODE        0X0005
SINE_TABLE
            addwf       PCL,F

            RETLW       .0
            RETLW       .4
            RETLW       .8
            RETLW       .16
            RETLW       .24
            RETLW       .34
            RETLW       .50
            RETLW       .64
            RETLW       .80
            RETLW       .96
            RETLW       .112
            RETLW       .128
            RETLW       .144
            RETLW       .156
            RETLW       .168
            RETLW       .178
            RETLW       .184
            RETLW       .188
            RETLW       .190

            END
```